INTERPLANETARY GUIDANCE SYSTEMS REQUIREMENTS STUDY

VOLUME II

COMPUTER PROGRAM DESCRIPTIONS

PART 5

NOMINAL ATMOSPHERIC ENTRY TRAJECTORIES

VERSION I

Prepared for
ERC Systems Laboratory
under Contract NAS 12-7

AC ELECTRONICS DIVISION
General Motors Corporation
El Segundo, California

31 July 1966

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ABSTRACT

This document describes a digital computer program developed to simulate the single pass and single skipout trajectories for a lifting-type vehicle during atmospheric entry. The description includes a mathematical model, a computer program description, a user's guide, an operator's and programmer's guide, a test case, and a program listing. The mathematical model describes the equations used in generating the trajectory. The computer program description includes flow charts and detailed equations, on which the development of the computer program was based. It was written in FORTRAN IV for the IBM 7094 system.

1.0 INTRODUCTION AND SUMMARY

The computer program defined by this document is designed to simulate the flight of a lifting vehicle during atmospheric entry. Single pass as well as single skipout trajectories can be simulated. It also forms the basis of the nominal and actual trajectory block as used in the performance assessment program for aided-inertial entry guidance systems. The basic assumptions and the general structure of the mathematical model are described in Section 2.

Section 3 contains flow charts describing the logical flow and detailed equations used in the program. The flow charts are designed to provide insight into the program operations at decreasing levels of logical and computational complexity. The highest level flow chart, Level I, depicts the basic functional structure of the program. Each block of this chart is broken into lower-level flow charts until no further logic has to described. The equations which are programmed are usually stated together with the lowest level flow charts.

Section 4 contains a user's guide which describes the modes of operation of the program and its capabilities. The input sheet is provided and a test case including input and sample output is provided.

Section 5 contains an Operator and Programmer Guide.

Section 6 lists technical references pertinent to the development of the program. To facilitate the interpretation of the program listing, contained in Appendix 7.2, transliterations between FORTRAN IV names and equation symbols are contained in Appendix 7.1.

2.0 MATHEMATICAL MODEL

2.1 BASIC ASSUMPTIONS AND GENERAL STRUCTURE OF TRAJECTORY PROFILE

The model for the nominal re-entry trajectory which provides acceleration, velocity, position, and attitide as a function of time for the performance assessment of aided-inertial re-entry guidance systems, as described below, is based upon the following general assumptions.

a. Physical Environment

Nonrotating planet with a spherically symmetric gravitational potential and and exponential nonrotating atmosphere constitutes the physical environment.

b. Vehicle Configuration

A rigid lifting vehicle without any thrusting capability outside that required for attitude changes is assumed.

c. Nominal Control

Aerodynamic control is achieved through a change of the roll angle. The control philosophy is dependent upon the specific phase and is described below in a phenomonological manner.

The mathematical model is formulated in such a fashion that at most seven phases can be encountered in one trajectory. On the other hand, it is possible that the starting point can lie in any of these phases. These phases are schematically depicted in Figure 1.

The model can describe the following major mission profiles:

a. Single-pass trajectories. This class encompasses those trajectories in which the vehicle does not leave the atmosphere after it entered it once.

b. Single-skipout trajectories. This class encompasses those trajectories for which two atmospheric phases are connected with each other by a free-fall orbit.

In addition to these two major classes the model provides the possibility of describing other trajectories such as those encountered in atmospheric braking maneuvers. The latter can be simulated by starting the program in phase 3.

For the sake of clarity, the different phases, as numbered in Figure 1 (i.e., assuming a single-skipout trajectory) are defined as follows.

Phase 1: Initial entry phase. A constant roll angle control policy is used during this phase. The sign of the roll angle is allowed to change so that the

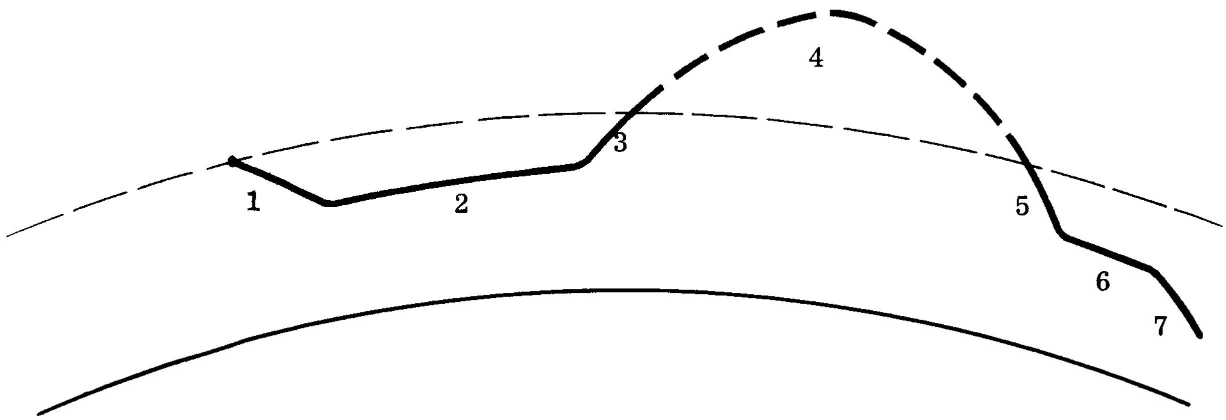


Figure 1. Trajectory Profile (Schematic)

vehicle will remain sufficiently near to its initial trajectory plane.

Phase 2: "First" constant altitude phase. The roll angle is changed such that the vehicle maintains constant altitude.

Phase 3: Pullout phase. The roll angle is changed according to a prespecified time history. This is done by specifying the coefficients of two second-order polynomials in time. The length of time that the two curve fit control laws are used may be specified. If the vehicle has a high enough speed and appropriate coefficients are specified, a path may be generated such that phase 4 will be entered.

Phase 4: Skipout phase. No trajectory control since it is assumed that thrust is only available for vehicle attitude control.

Phase 5 and 6: Second entry phase and second constant altitude phase. The control policies are equivalent to those in phases 1 and 2, respectively.

Phase 7: Final descent phase. The vehicle is kept at constant roll angle and angle of attack. The roll angle can change signs in order to provide out-of-plane control.

2.2 COORDINATE SYSTEMS

The initial position and velocity of the vehicle with respect to the re-entry planet may be input in either cartesian or spherical coordinates. These coordinate systems are shown in Figure 2. The cartesian system is right-handed, irrotational, and orthogonal. The axes may be considered to be oriented with the $\underline{k}$ axis along the northern polar axis of the re-entry planet and the $\underline{i}$ and $\underline{j}$ axis in the equatorial plane. However, this orientation is arbitrary since the planet is assumed to be a nonrotating spherical body. All the velocity and acceleration integrations are performed in the $\underline{i}$, $\underline{j}$, $\underline{k}$ coordinate system.

If the $\underline{i}$, $\underline{j}$, $\underline{k}$ cartesian coordinate system is considered to have the orientation described above, the input spherical coordinate system would have the following meaning:

r_o - radial distance of vehicle from center of re-entry planet

u_o - longitude

λ_o - latitude

V_o - speed

γ_o - flight path angle, measured from the local horizontal plane up to the velocity vector

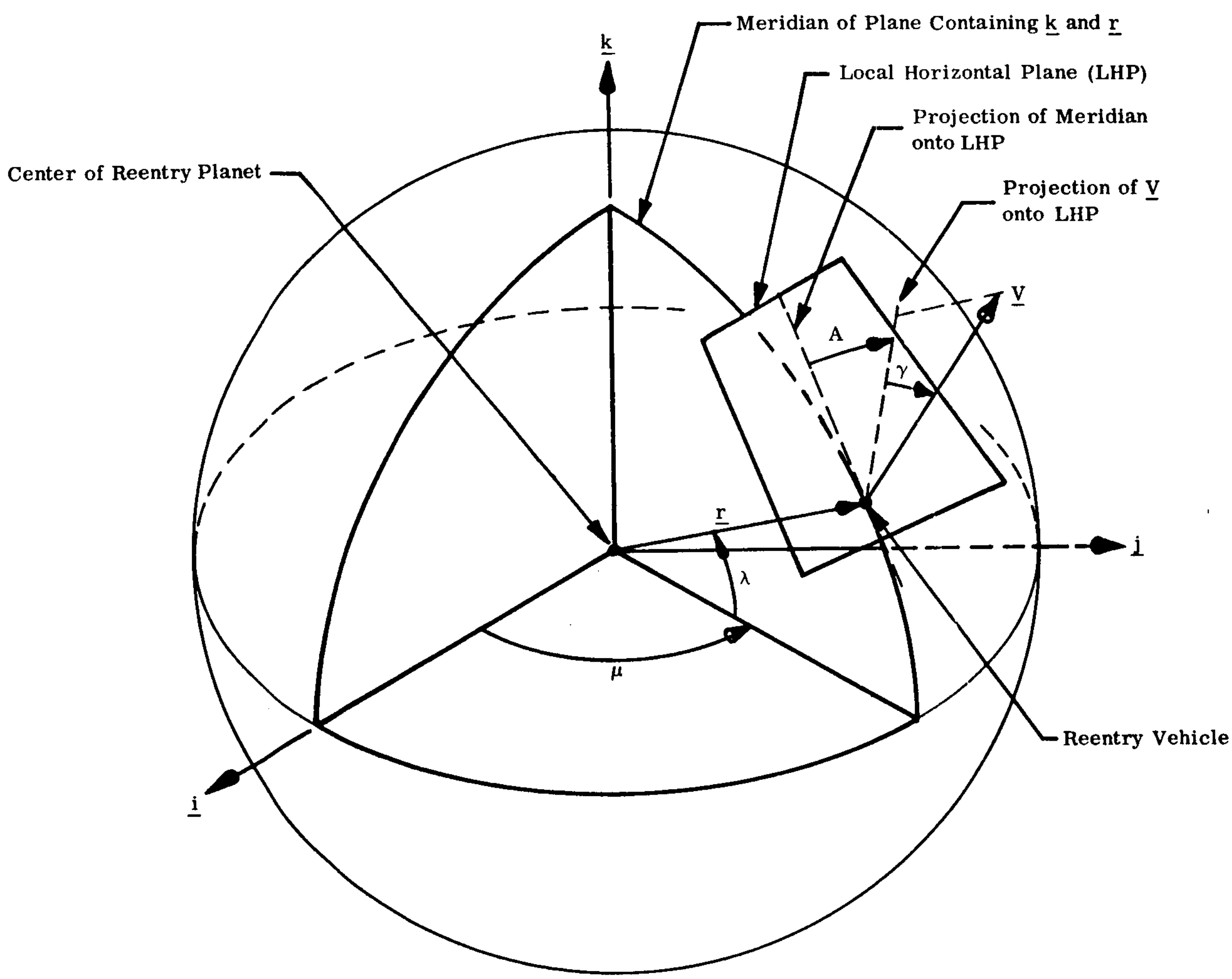
A_o - azimuth angle, measured clockwise from north to the projection of the velocity vector in the local horizontal plane

The output position and velocity are given in both the $\underline{i}$, $\underline{j}$, $\underline{k}$ cartesian system and a second spherical coordinate system as shown in Figures 3 and 4. This second spherical system is convenient because it is oriented in the initial trajectory plane. This provides direct observation of out-of-plane velocity and position values.

The output spherical system, r, θ, φ, V, γ, β, is referenced to the right-handed, irrotational, orthogonal cartesian coordinate system, $\underline{i}_t$, $\underline{j}_t$, $\underline{k}_t$. The relation between the $\underline{i}$, $\underline{j}$, $\underline{k}$ system and the $\underline{i}_t$, $\underline{j}_t$, $\underline{k}_t$ system is shown in Figure 3. The relation between the $\underline{i}_t$, $\underline{j}_t$, $\underline{k}_t$ system and the r, θ, φ, V, γ, β system is shown in Figure 4.

The $\underline{i}_t$, $\underline{j}_t$, $\underline{k}_t$ system is set up at the beginning of the program ($t = t_o$) with $\underline{j}_t$ and $\underline{k}_t$ forming the initial trajectory plane so that the output spherical system will have the following interpretation:

r - radial distance of vehicle from center of re-entry planet



Input:

TRINP = 1: Position = $X_0\underline{i} + Y_0\underline{j} + Z_0\underline{k}$
Velocity = $\dot{X}_0\underline{i} + \dot{Y}_0\underline{j} + \dot{Z}_0\underline{k}$

TRINP = 0: Position = $r_0,\ \lambda_0,\ \mu_0$
Velocity = $V_0,\ \gamma_0,\ A_0$

Figure 2. Input Coordinate Systems

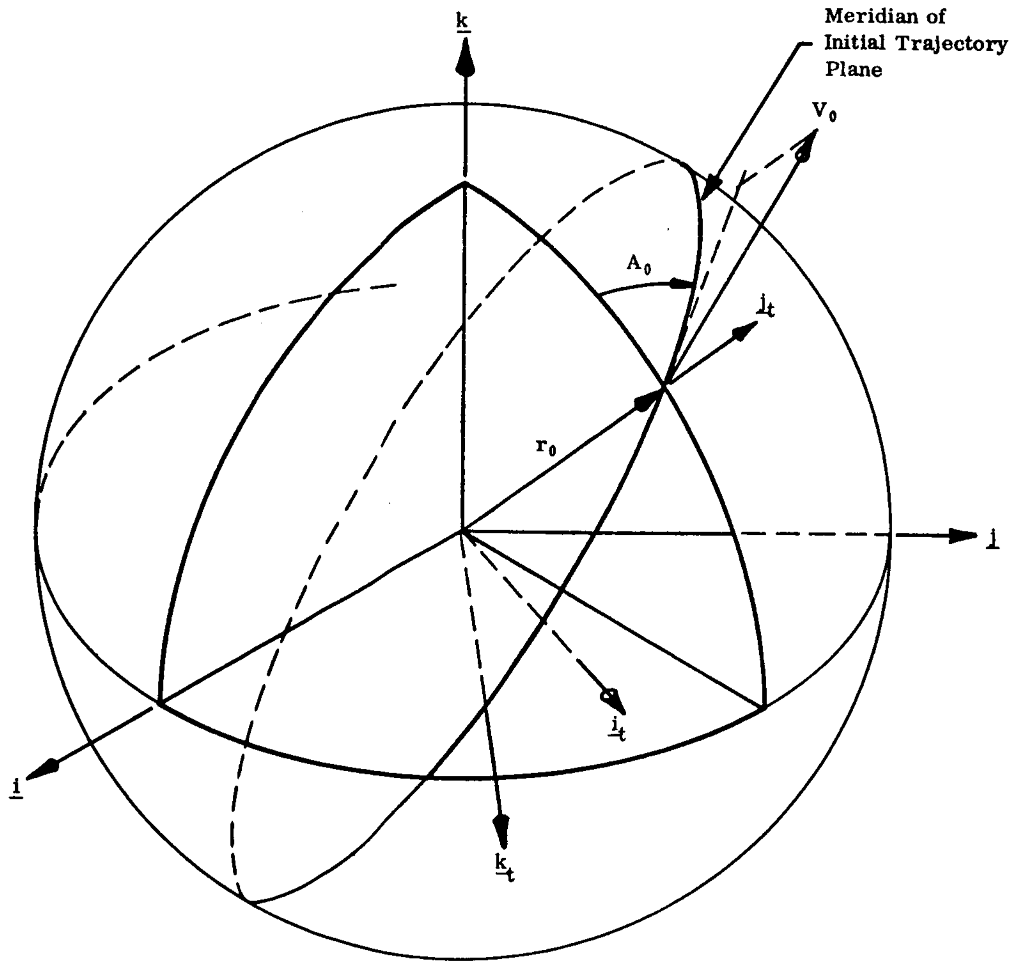
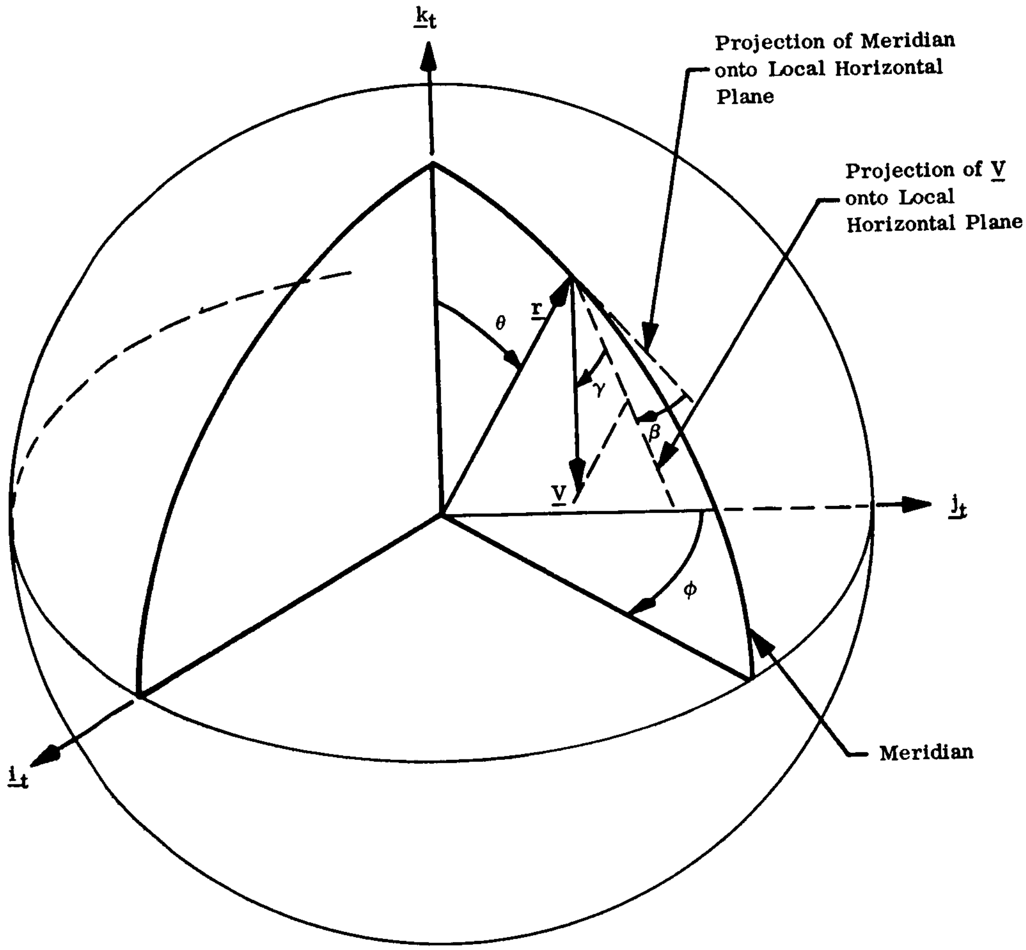


Figure 3. Cartesian Basis for Output Spherical Coordinate System at $t = t_o$ ($\underline{i}_t$, $\underline{j}_t$, $\underline{k}_t$) related to $\underline{i}$, $\underline{j}$, $\underline{k}$ system



NOTE: Since θ = range angle +90°, θ is never less than 90°. However, the diagram was drawn as it is for clarity.

The unit vectors $\underline{i}_t$ and $\underline{k}_t$ form the initial trajectory plane.

Figure 4. Relation Between Spherical Output Coordinate System (r, θ, ϕ, V, γ, β) and $\underline{i}_t, \underline{j}_t, \underline{k}_t$ system (at $t \neq t_o$)

θ	- range angle plus 90 degrees
φ	- out-of-plane position angle
V	- speed
γ	- flight path angle
β	- angle between the projection of the velocity vector onto the local horizontal plane and the plane formed by $\underline{k}_t$ and $\underline{r}$, measured clockwise from the plane

The orientation of the vehicle is given by three orthogonal unit vectors defining the pitch axis ($\underline{P}_I$), the yaw axis ($\underline{Y}_A$), and the roll axis ($\underline{R}_O$). There are three sets of these unit vectors. One set is the actual set ($\underline{P}_I$, $\underline{Y}_A$, $\underline{R}_O$) which describe the current orientation of the vehicle. A second set is the reference set ($\underline{P}I_O$, $\underline{Y}A_O$, $\underline{R}O_O$) which is defined with respect to the $\underline{i}$, $\underline{j}$, $\underline{k}$ coordinates by the matrix transformation (A_4) shown in Block B. 1. 4. The third set is the set defining the orientation of the vehicle with respect to the reference set at time $= t_o$ ($\underline{P}_I$, $\underline{Y}_A$, $\underline{R}_O$)$_{t = t_o}$. The initial orientation is different from the reference set by the Euler angles α_{1o}, α_{2o}, α_{3o} (input quantities).

The roll axis ($\underline{R}_O$) is different from the direction of the velocity vector by the angle of attack (α). Also, the pitch axis ($\underline{P}_I$) is rotated from a line perpendicular to the trajectory plane by the angle $90^\circ - \varphi$. These conditions remain true throughout the flight.

2.3 DIFFERENTIAL EQUATIONS OF MOTION

This section states the differential equations of motion, resulting from the following basic assumptions:

a. The vehicle is represented by a point mass.

   This assumption concerns only the motion of the vehicle along the trajectory. The 6-dimensional dynamical character of the problem is taken into account through the model for the nominal control policy, as described in the next section. It enters the differential equations directly through the control variables which are the roll angle φ, and the angle of attack α.

b. Ablation effects are ignored resulting in the assumption of constant mass.

c. Exponential nonrotating atmosphere and spherical earth are assumed.

Under these assumptions the differential equations of motion in the cartesian ($\underline{i}$, $\underline{j}$, $\underline{k}$) coordinate systems becomes

$$\underline{a} = \frac{1}{M}(\underline{D} + \underline{N}) - \underline{g}$$

$\underline{a}$ is the total acceleration, M the access of the vehicle, $\underline{g} = g_o(\frac{R}{r})\,\underline{U}_r$ is the gravitational acceleration with

g_o	= sea level gravitational acceleration of re-entry planet
R	= radius of re-entry planet
r	= radial distance of re-entry vehicle from center of re-entry planet
$\underline{U}_r$	= unit position vector of vehicle in the Newtonian reference cartesian coordinate system, $\underline{i}$, $\underline{j}$, $\underline{k}$

The aerodynamic drag forces $\underline{D}$ and the aerodynamic normal force $\underline{N}$ are given by

$$\underline{D} = -\,C_D\,\rho\,\frac{V^2 S}{2}\,\underline{U}_v$$

$$\underline{N} = C_N\,\rho\,\frac{V^2 S}{2}\,(\cos\varphi\,\underline{U}_u - \sin\varphi\,\underline{U}_p)$$

The dependence of the aerodynamic drag and normal force coefficients C_D and C_N on the angle of attack α is assumed as

$$C_D = C_{D_o} + C_2\alpha^2 + C_4\alpha^4$$

$$C_N = C_{N_\alpha} + C_3\alpha^3 + C_5\alpha^5$$

where C_{D_o}, C_{N_α}, and C_i $(i = 2, \ldots, 5)$ are properly chosen constants.

The atmosphere density has the form

$$\rho = \rho_o\,e^{-\beta'(r - R)}$$

V indicates the speed, S the aerodynamic area of the vehicle, and the orthogonal (u, v, p) coordinate system is defined as

$\underline{U}_u$	unit vector in direction of velocity
$\underline{U}_v$	unit vector perpendicular to $\underline{U}_v$ and in instantaneous trajectory plane
$\underline{U}_p$	$= \underline{U}_u \times \underline{U}_v$

This completes the description of the differential equations in the $(\underline{i}, \underline{j}, \underline{k})$ coordinate system. The equations of motion are always integrated with respect to this coordinate system.

2.4 INTEGRATION ROUTINE

Time is advanced in the program by the integration routine. The integration loop consists of the integration routine (Block I. 4 - Range Kutta Type), dynamics block (Block I. 2), and the evaluation block (Block I. 8). This loop is exited to calculate a new nominal control at each nominal control time, phase change time, print time, and the terminate run time.

2.5 NOMINAL CONTROL

Only the roll angle φ is used for aerodynamical control of the vehicle in the different phases as explained in the first section. The quantitative details are discussed phasewise below.

2.5.1 Nominal Control During First and Second Re-entry Phase

A constant roll angle is used in these two phases and is changed in sign if the direction of the velocity vector deviates from the initial nominal trajectory plane by more than ϵ_s. Thus

$$\varphi_{ci} = \text{sign}_i \, \varphi_c$$

$$\text{sign}_i = \begin{cases} \text{sign}_{i-1} \text{ if } |\underline{U}_{p_o} \cdot \underline{U}_v| < \epsilon_s \\ \text{sign}\,(\underline{U}_{p_o} \cdot \underline{U}_v) \text{ if } |\underline{U}_{p_o} \cdot \underline{U}_v| \geq \epsilon_s \end{cases}$$

where

$$\underline{U}_{p_o} = (\underline{U}_u \times \underline{U}_v)_{t_o}$$

defines the unit vector normal to the initial trajectory plane.

During a flipover maneuver, the change in the roll angle is assumed to be

$$\varphi_i = \varphi_{i-1} + \omega_{\varphi_{i-1}} \Delta t$$

and the roll rate of the vehicle is computed according to

$$\omega_{\varphi_i} = K_\varphi (\varphi_{ci} - \varphi_i)$$

K_φ is a preselected constant, representing in a gross fashion the vehicle response to the control system.

2.5.2 Nominal Control During the Constant Altitude Phases

The roll angle control is given by

$$\varphi_c = \text{sign}_i \left[\frac{\pi}{2} + \sin^{-1} (K_1 \Delta\dot{r} + K_2 \Delta r) + \frac{\pi}{2} e^{-K_3 (t - T_c)} \right]$$

where

$\Delta\dot{r} = \dot{r}$ = radial velocity of vehicle

$\Delta r = r - r_c$

r_c = desired constant altitude of vehicle

K_1 and K_2 are gains whose value is either input as constant or calculated as a function of time (optimum gains)

K_3 is an input constant

T_c = time at the beginning of the constant altitude phase

sign_i is chosen in the same fashion as in the initial entry phases and provides out-of-plane control

This control law provides upward normal force ($|\varphi_c| < \pi/2$) as required to keep the vehicle at a constant altitude. The term

$$(\pi/2) e^{-K_3 (t - T_c)}$$

is used to make $|\varphi_c| = \pi$ at the beginning of the constant altitude. This is helpful in preventing an unintentional skipout.

The following scheme was used to calculate the gains K_1 and K_2 as a function of time: In order that the radial velocity be zero and the radial distance not vary from some desired value (r_c) the following restriction was placed on the commanded roll angle:

$$\sin (\varphi_c - 90°) - [K_1 (\dot{r} - 0) + K_2 (r - r_c)] = 0 \qquad (1)$$

Equating the radial acceleration to the acceleration provided by the normal force (normal to the drag force) gives the following:

$$- \Delta\ddot{r} = \frac{1}{M} N \sin (\varphi - 90°) \qquad (2)$$

where

φ = roll angle of vehicle

M = mass of vehicle

N = magnitude of normal force

$\Delta\ddot{r} = \ddot{r}$ = radial acceleration

Substituting (2) into (1) gives

$$\Delta\ddot{r} + \frac{N}{M} K_1 \Delta\dot{r} + \frac{N}{M} K_2 \Delta r = 0$$

which is analogous to the standard second-order differential equation

$$\ddot{x} + 2\zeta \frac{2\pi}{\tau} \dot{x} + \frac{4\pi^2}{\tau^2} = 0$$

where ζ is the damping ratio and

τ is the natural period of oscillation

Thus we may set

$$K_1 = \frac{4\pi M \zeta}{N\tau} \qquad \text{and} \qquad K_2 = \frac{4\pi^2 M}{N\tau^2}$$

and input values of ζ and τ such that the constant altitude control policy will have the desired values of damping and oscillation frequency.

2.5.3 Nominal Control in Pullout Phase

The roll angle is used as a control variable and is specified as

$$\varphi_c = \text{sign}_i \left[F_0 + F_1 (t - T'_c) + F_2 (t - T'_c)^2\right]$$

F_0, F_1, and F_2 are appropriate input quantities; T'_c the time at beginning of pullout phase. Sign_i is determined as in the initial entry phase and used for out-of-plane control.

2.5.4 Nominal Control in Final Descent Phase

The roll angle is used as a control variable in the same way as in the initial entry phase.

2.6 EVALUATION

The calculation of heating and pilot acceleration history is performed in the evaluation block (Block I.8). By looking at the output of these values (Q and E_n, respectively) a particular trajectory may be evaluated concerning the severity of ablation on the vehicle and the aerodynamic acceleration effects experienced by the pilot.

Convective heating rate at the stagnation point is calculated as follows.

$$q_c = \frac{C_H}{\sqrt{R_N}} \left(\frac{\rho}{\rho_o}\right)^n \left(\frac{V}{\sqrt{gr}}\right)^m$$

where

q_c	= convective heating rate
C_H	= an input constant whose value depends on the planet's atmosphere and the type of boundary layer flow
n	= an input constant describing boundary flow ($n = 0.5 \rightarrow$ laminar flow)
m	= an input constant describing the type of flow ($m = 3 \rightarrow$ laminar flow)
R_N	= radius of curvature of vehicle at stagnation point

Radiative heating rate at the stagnation point is calculated as follows.

$$q_r = k_H R_N \left(\frac{\rho}{\rho_o}\right)^{p_H} C_e V^q$$

where

q_r	= radiative heating rate
k_H	= an input constant specifying the percentage of heat radiation between the gas cap and the vehicle
p_H	= an input quantity

$$C_e = \begin{cases} C_{e1} \text{ if } \dfrac{V}{\sqrt{gr}} < 1.73 \\ C_{e2} \text{ if } \dfrac{V}{\sqrt{gr}} \geq 1.73 \end{cases}$$

C_{e1}, C_{e2} are input qu ntities

$$q = \begin{cases} q_1 \text{ if } \dfrac{V}{\sqrt{gr}} < 1.73 \\ q_2 \text{ if } \dfrac{V}{\sqrt{gr}} \geq 1.73 \end{cases}$$

q_1 and q_2 are input quantities

The total stagnation point heating rate is given by

$$q_s = q_c + q_r$$

The accumulated heat which can be used as a measure of ablative losses is given by

$$Q = \int_{t_o}^{t} q_s \, dt$$

where Q is an output quantity.

The limit of pilot acceleration endurance is represented by

$$\tau' = E_0 + E_1 a' + E_2 (a')^2 + E_3 (a')^3 + E_4 (a')^4$$

$$a' = f/g_e$$

where

τ'	= length of time a pilot will remain usefully conscious at a particular acceleration level
a'	= aerodynamic acceleration in earth g's
f	= aerodynamic acceleration of vehicle
g_e	= sea level gravitational acceleration of earth
E_i (i=0, 4)	= input quantities

The acceleration history of the pilot is represented by

$$E_n = \int_{t_o}^{t} \dot{E}_n \, dt, \text{ where } \dot{E}_n = \begin{cases} \frac{1}{\tau'} & \text{if } \frac{1}{\tau'} > 0.0008 \\ 0 & \text{if } \frac{1}{\tau'} \leq 0.0008 \end{cases}$$

Thus if the value of E_n ever reaches or exceeds one, the pilot has "lost" useful consciousness. However, the program will not stop on this condition.

3.0 COMPUTER PROGRAM DESCRIPTION

3.1 INTRODUCTION AND GENERAL EXPLANATION

Flow charts provide the basic framework around which the discussion below is constructed. These diagrams serve to indicate the logical flow connecting different functional blocks.

The flow charts have been arranged and drawn according to a hierarchical structure. The "highest" level, designated as Level I, depicts the overall structure of the program. Each block appearing in this chart is described by another flow chart. These charts are designated as Level II. This policy is repeated for each block in every level until no further logic remains to be described. The final set of flow charts at the lowest level are supplemented by the detailed equations which are used in the program.

3.1.1 Flow Chart Organization

As has already been stated, the flow charts are arranged according to "levels". In the resulting hierarchy, the Level I flow chart provides the most general description since it depicts the overall program. Each functional block is further described by lower level flow charts. These charts indicate the logical flow within the block and describe the input and output requirements of the block. The equations used to obtain the desired outputs are presented as a supplement to the lowest level flow chart.

LEVEL I: This flow chart is designed to provide a very general description of the entire program. The titles assigned to the functional blocks are intended to be suggestive of the nature of the role to be performed within the block. Those functions that are to be performed in the basic computational cycle are designated by Roman numerals. Arabic symbols are used for functions that occur only once or play a passive role.

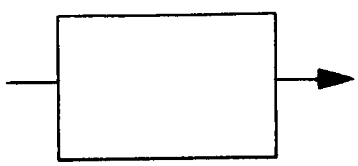
To indicate the basic logical decisions that can regulate and alter the flow between functional blocks, decision blocks are indicated. These decisions represent in a general manner the types of decisions that are required. The actual decision logic is described in the Level II flow charts of the functional blocks immediately preceding the decision block.

LEVEL II: The Level II flow charts provide the first concrete description of the program. Only the most important logical flow within each functional block is indicated on these diagrams. The quantities that are required for all logical and computational operations within this block are stated on this chart. These quantities are differentiated as being either INPUT (i. e., values provided initially by the engineer) or COMPUTED (i. e., values determined in other portions of the program). The quantities that are required in other parts of the program are also indicated on this flow chart. The functional blocks that appear on these diagrams are denoted by two symbols (e.g., II. 1 when discussing the "first" block in the Level II flow chart of functional block II) and a name. The names have been selected to provide some insight into the nature of the block.

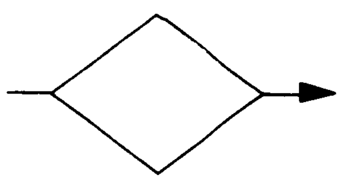
LEVEL III: These diagrams provide additional details of the logic flow within the functional blocks depicted at Level II. These flow diagrams are augmented by the equations programmed into the computer. The input and output requirements of these blocks are stated on the diagrams. All of these quantities are summarized in the Level II flow chart.

3.1.2 Definition of Flow Chart Symbols

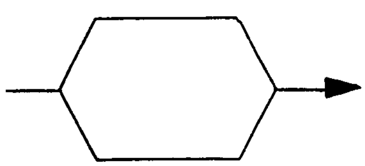
The following symbols represent the only ones that are used in the flow charts presented below.



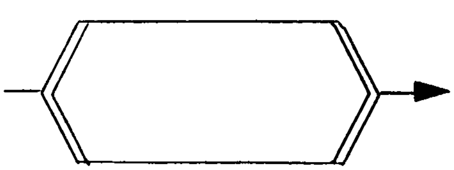
Set of operations that is to be described further by additional flow charts or by equations



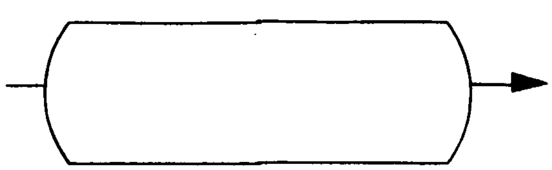
Logical decision



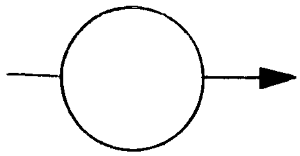
Operations that are predefined (i.e., in some other document)



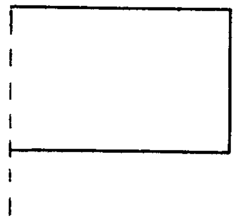
Operations are completely defined by the statements contained within the box



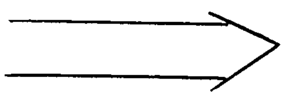
Connector used on Level II flow charts to indicate entry source and exit destination



Connector used on Level III flow charts



Summary of all quantities required in computations of flow charts on which this symbol appears or, alternatively, summary of all quantities computed in this flow chart which are required in other operations



This broad arrow appears on Level I and Level II flow charts. It is used to indicate information flow from one block to another. This symbol has been introduced to emphasize that many quantities are transmitted between the functional blocks in the higher level charts.

3.1.3 Definition of Equation Symbols

The symbols used in the subsequent flow charts and equations are defined below. These symbols appear in three groups: flags, Roman letter symbols, and Greek letter symbols. The dimensions are given in parenthesis following the definition. M denotes a dimension of mass, L a dimension of length, and T a dimension of time. If no designation is given, the quantity is unitless, and an R indicates an angular measure in radians.

FLAGS

TRACC (input quantity) Constant altitude control flag. This flag specifies the manner in which the program switches to constant altitude control (phases 2 and 6)

0 - program switches to constant altitude control when $\dot{r} = 0$

1 - program switches to constant altitude control when

$$r < C_{apc}\, g_o \ \underline{\text{and}}\ \dot{r} > C_{vpc} \sqrt{g_o R}$$

where C_{apc} and C_{vpc} are input quantities. The program will always switch to constant altitude control on $\dot{r} = 0$ if $\dot{r} = 0$ before $\ddot{r} < C_{apc}\, g_o$ or $\dot{r} > C_{vpc} \sqrt{g_o R}$

TRBAK — End of run flag. This flag is set by the program to determine the point at which a run is to be terminated.

TRCRi — ($i = 1, 2, 3, 4$) Minimum NEXTTi flag. When TRCRi = 1, the time NEXTTi is the minimum of the NEXTTi, $i = 1, 2, 3, 4$. If two or more of the NEXTTi are minima, the appropriate TRCRi flags will be set to 1.

TRGUID — Nominal control flag. When this flag is set to 1, a new nominal control is calculated (i.e., the nominal control block is entered).

TRINP — (input quantity) Coordinate system type flag.

- 0 - initial position and velocity are input in spherical components (r_o, λ_o, μ_o, V_o, γ_o, A_o).
- 1 - initial position and velocity are input in cartesian components (X_o, Y_o, Z_o, $\dot{X}_o$, $\dot{Y}_o$, $\dot{Z}_o$).

TROPGN — (input quantity) Time-varying gains computation flag. The control gains used in the constant altitude phases are computed as a function of time if this flag is set.

- 0 - input gains as constants (K_{11}, K_{12}, K_{21}, K_{22})
- 1 - compute gains as a function of time. Input damping ratio (ζ_1, ζ_2) and oscillation period (τ_1, τ_2)

TRPHSE — (input quantity) Mission phase flag. The value of this flag corresponds to the phase of the nominal trajectory that the vehicle is currently in. This is an input quantity and the program may be started in any phase.

- 1 - first supercircular velocity phase
- 2 - first constant altitude phase
- 3 - skipout control phase
- 4 - free-fall phase
- 5 - second supercircular velocity phase
- 6 - second constant altitude phase
- 7 - subcircular velocity phase

TRPNT — Print flag (set within program)

- 0 - printout does not occur
- 1 - printout occurs

TRSBCL (input quantity) Start subcircular velocity phase (7).

0 - if the program is presently in phase 6, then phase 7 will start when $\dot{r} \leq 0$ and $|\varphi| \leq 10^{-2}$

1 - if the program is in phase 6, then phase 7 will start when $V = V_{IN}$

TRSKIN Skip integration flag. This flag is used in the program to avoid the possibility of integrating "backwards"

Constants and Variables

$\underline{a}$ Vehicular acceleration. This vector has components $\ddot{X}$, $\ddot{Y}$, $\ddot{Z}$ along the $\underline{i}$, $\underline{j}$, $\underline{k}$ axes, respectively. (LT^{-2})

a Magnitude of $\underline{a}$. (LT^{-2})

a' Aerodynamic acceleration of vehicle in Earth g's.

a_e Semi-major axis of a two-body conic trajectory calculated in phase 4. (L)

A_o (input quantity) Initial azimuth of vehicle (part of initial velocity input). Used only when TRINP = 0. (R)

A_2 Orthonormal matrix transformation relating the body axes at $t = t_o$ $(\underline{P}_I, \underline{Y}_A, \underline{R}_O)_{t = t_o}$ to the $\underline{i}$, $\underline{j}$, $\underline{k}$ coordinate system.

A_3 Orthonormal matrix transformation defining the reference body axis $(\underline{P}_{Io}, \underline{Y}_{Ao}, \underline{R}_{Oo})$ in terms of the initial body axes $(\underline{P}_I, \underline{Y}_A, \underline{R}_O)_{t = t_o}$.

A_4 Orthonormal matrix transformation relating the reference body axes $(\underline{P}_{Io}, \underline{Y}_{Ao}, \underline{R}_{Oo})$ to the $\underline{i}$, $\underline{j}$, $\underline{k}$ coordinate system.

A_5 Orthonormal matrix transformation relating an initial local coordinate system $(\underline{i}_t, \underline{j}_t, \underline{k}_t)$ to the $\underline{i}$, $\underline{j}$, $\underline{k}$ coordinate system.

C_{apc} (input quantity) A quantity used to form $\ddot{r}_{pc}$ $(\ddot{r}_{pc} = C_{apc}\, g_o)$ which is compared to radial acceleration. Used only if TRACC = 1. If $\ddot{r}_{pc} \geq \ddot{r}$ then a test is made on $\dot{r}$ to see if the program should switch from phase 1 to 2 or from phase 5 to phase 6. If $\ddot{r}_{pc} < \ddot{r}$, the program will switch to phases 2 or 6 when $\dot{r} = 0$.

C_{vpc}	(input quantity) A quantity used to form r_{pc} ($\dot{r}_{pc} = C_{vpc} \sqrt{g_o R}$) used only if TRACC = 1. If $\ddot{r}_{pc} \geq \ddot{r}$ and $\dot{r}_{pc} \leq \dot{r}$, then the program switches to phases 2 or 6.
C_D	Drag force ($\underline{D}$) coefficient as a function of α (angle of attack) ($C_D = C_{Do} + C_2\alpha^2 + C_4\alpha^4$).
C_{Do}, C_2, C_4	(input quantities) Coefficients of C_D.
C_N	Normal force ($\underline{N}$) coefficient as a function of α (angle of attack) ($C_N = C_{N\alpha} + C_3\alpha^3 + C_5\alpha^5$).
$C_{N\alpha}, C_3, C_5$	(input quantities) Coefficients of C_N.
C_{e1}	(input quantity) A constant used to calculate vehicle radiative heating (q_r). $C_e = C_{e1}$ when $(V/\sqrt{g\,r}) < 1.73$. ($M\ L^{-1-q_1}\ T^{q_1-3}$).
C_{e2}	(input quantity) A constant used to calculate vehicle radiative heating (q_r). $C_e = C_{e2}$ when $(V/\sqrt{g\,r}) \geq 1.73$. ($M\ L^{-1-q_2}\ T^{q_2-3}$).
C_e	A constant used to calculate radiative vehicle heating (q_r). For velocity dependence and units see C_{e1} and C_{e2}.
C_H	(input quantity) A constant used to calculate stagnation point convective heating rate, q_c. Its value depends on the planetary atmosphere and the type of boundary layer flow. ($M\ L^{1/2}\ T^{-3}$; e.g., English units → BTU $ft^{-3/2}\ sec^{-1}$)
$C_{\zeta\tau 1}, C_{\zeta\tau 2}$	Constants used to generate a commanded roll angle in the constant altitude control phases (2 and 6). (MT^{-1}, T^{-1})
$\underline{D}$	Drag force. The aerodynamic force in the direction of negative velocity ($\underline{i}$, $\underline{j}$, $\underline{k}$ coordinates). ($M\ L\ T^{-2}$)
D	Magnitude of drag force. ($M\ L\ T^{-2}$)
e	Eccentricity of elliptical path in free-fall phase (4).
E_i	(input quantities; i = 0, 1, 2, 3, 4) Coefficients of fourth order polynominal in a' defining the maximum time a pilot can remain usefully conscious.
E_n	Integral of the ratio of the time a pilot spent at various acceleration levels to his maximum time of useful consciousness at those levels. When $E_n > 1$, the pilot has exceeded this tolerance level.

$\dot{E}_n$	Reciprical of time interval that a pilot can remain usefully conscious at a particular acceleration level. (T^{-1})
$\underline{f}$	Aerodynamic acceleration vector of the vehicle ($\underline{i}$, $\underline{j}$, $\underline{k}$ coordinates). (LT^{-2})
f	Magnitude of aerodynamic acceleration of the vehicle. (LT^{-2})
F_i	Constants defining the desired roll angle during the skipout control phases (3 and 3 modified). The units are: at $i = 0$, unitless at $i = 1$, T^{-1} at $i = 2$, T^{-2}
F_{1i}	(input quantities, $i = 0, 1, 2$) F_i has these values during $t_3 \leq t < t'_3$ (phase 3). (unitless, T^{-1}, T^{-2})
F_{2i}	(input quantities) F_i has these values during $t'_3 \leq t < t_4$ (phase 3 modified). (unitless, T^{-1}, T^{-2})
g	Vehicular acceleration due to gravitational attraction of the re-entry planet ($g = g_o (R/r)^2$). (LT^{-2})
g_e	(input quantity) Sea level gravitational acceleration of earth. (LT^{-2})
g_o	(input quantity) Sea level gravitational acceleration of re-entry planet. (LT^{-2})
G_{max}	(input quantity) Limit on aerodynamic deceleration of the vehicle in earth g's. If this limit is exceeded during phases 1, 2, 5, or 6, the run is terminated.
h	Altitude above surface of re-entry planet (planet assumed to be spherical). (L)
I (X)	A functional notation meaning the integer part of X.
$\underline{i}$, $\underline{j}$, $\underline{k}$	An irrotational right-handed coordinate system of unit vectors. $\underline{i}$ and $\underline{j}$ are in the equatorial plane and $\underline{k}$ is along the polar axis. $\underline{i}$ is oriented so that the $\underline{i}$ $\underline{k}$ plane is the zero longitude meridian. Integration is performed in this cartesian coordinate system.

$\underline{i}_t, \underline{j}_t, \underline{k}_t$ — An irrotational right-handed coordinate system which is defined at the start of the simulation (time = t_o). The initial trajectory plane defines the $\underline{j}_t$, $\underline{k}_t$ plane with the $\underline{j}_t$ vector colinear with the initial radial distance vector ($\underline{r}_o$). This coordinate system allows direct observation of out-of-plane components of position and velocity.

k_H — (input quantity) Used in the calculation of radiative vehicle heating.

K_1, K_2 — Constant altitude guidance gains. Used to generate a commanded roll angle such that the vehicle will remain at a constant altitude during phases 2 and 6. ($L^{-1}T$, L^{-1})

K_3 — Used to make the commanded roll angle have a transient value of π at the beginning of phases 2 and 6. If $K_3 > 10$, the transient is not applied. (T^{-1})

K_{11}, K_{12}, K_{13} — (input quantities) K_1, K_2, and K_3 have these values in phase 2. ($L^{-1}T$, L^{-1}, T^{-1})

K_{21}, K_{22}, K_{23} — (input quantities) K_1, K_2, and K_3 have these values in phase 6. ($L^{-1}T$, L^{-1}, T^{-1})

K_φ — (input quantity) Pseudo autopilot gain. K_φ times the difference between the commanded roll angle and the present roll angle is the angular rate at which the vehicle will roll (up to a limit - see β_φ). (T^{-1})

M — (input quantity) Mass of the vehicle. The mass is assumed constant throughout re-entry ignoring ablation effects. (M)

m — (input quantity) An exponent used in the calculation of convective heating rate (q_c) at the stagnation point. For laminar flow m = 3 corresponds to a gas with viscosity proportional to the square root of temperature.

n — (input quantity) An exponent used in the calculation of convective heating rate (q_c) at the stagnation point. Laminar flow is described by n = 1/2.

$\underline{N}$ — Normal aerodynamic force. The aerodynamic force on the vehicle which is normal to the drag force ($\underline{D}$). The orientation of this vector ($\underline{i}$, $\underline{j}$, $\underline{k}$ coordinates) is determined by the roll angle (φ). (MLT^{-2})

N — Magnitude of $\underline{N}$ (normal aerodynamic force). (MLT^{-2})

N_{SP}	A program flag set to print the appropriate special condition number when the program stops on a special condition. See the User's Guide for a description of special condition program halts.
NEXTTi	A set (i = 1, 2, 3, 4) of program variables which are set equal to various significant program times. NEXTT1 = next time at which nominal control will be calculated NEXTT2 = next time at which a printout is called for NEXTT3 = next time at which a phase change will occur NEXTT4 = time at which a special condition has been encountered unless NEXTT4 = T_{END}
p	Semi-latus rectum of elliptical path of vehicle in free-fall phase (4). (L)
p_H	(input quantity) An exponent used to calculate radiative vehicle heating.
$\underline{P}$	Unit vector in direction of the pericenter ($\underline{i}$, $\underline{j}$, $\underline{k}$ coordinates).
$\underline{P}_I$, $\underline{Y}_A$, $\underline{R}_O$	Orthonormal right-handed set of unit vectors along the pitch, yaw, and roll axes, respectively.
$\underline{P}_{Io}$, $\underline{Y}_{Ao}$, $\underline{R}_{Oo}$	Reference for body axes. These are not the same as $\underline{P}_I$, $\underline{Y}_A$, $\underline{R}_O$ at $t = t_o$ unless $\alpha_{10} = \alpha_{20} = \alpha_{30} = 0$.
q_1	(input quantity) An exponent used to calculate radiative vehicle heating (q_r). $q = q_1$ when $(V/\sqrt{gr}) < 1.73$.
q_2	(input quantity) An exponent used to calculate radiative vehicle heating (q_r). $q = q_2$ when $(V/\sqrt{gr}) \geq 1.73$.
q	An exponent used to calculate radiative vehicle heating (q_r). For velocity dependence see q_1 and q_2.
q_c	Convective heating rate per unit area at the stagnation point. $(M\ T^{-3})$
q_r	Radiative heating rate per unit area at the stagnation point. $(M\ T^{-3})$
q_s	Total heating rate per unit area at the stagnation point $(q_c + q_r)$. $(M\ T^{-3})$

Q	The time integral of the total vehicle heating rate per unit area at the stagnation point (q_s). Q is proportional to the total heat absorbed by the vehicle. $(M\ T^{-2})$
$\underline{r}$	Current position vector of vehicle ($\underline{i}$, $\underline{j}$, $\underline{k}$ coordinates). (L)
$\underline{r}_t$	Current position vector of vehi cle in an initial coordinate system set up at $t = t_o$, ($\underline{i}_t$, $\underline{j}_t$, $\underline{k}_t$ coordinates). (L)
r_o	(input quantity) Initial ($t = t_o$) radial distance of vehicle from center of re-entry planet. When TRINP = 0, r_o is input as part of the initial position coordinates. (L)
$\underline{r}_a$	Apocenter distance calculated at the beginning of phase 4. This is the maximum distance the vehicle will have from the center of the re-entry planet in phase 4 ($\underline{i}$, $\underline{j}$, $\underline{k}$ coordinates). (L)
r_a	Magnitude of $\underline{r}_a$. (L)
r_c	(input quantity) Radial distance of the vehicle from the center of the re-entry planet at the beginning of phases 2 or 6. This quantity must be input only if the program is started in phases 2 or 6. (L)
r_m	(input quantity) If $r > r_m$ and $\dot{r} > 0$ in phases 1, 2, 5, or 6, the run will end. (L)
r_{ma}	(input quantity) If r_a (apocenter distance) $> r_{ma}$ in phase 4, the run will end. For earth re-entry, this value would probably be set equal to the radial distance of the lowest Van Allen radiation belt from the center of the earth. (L)
r_p	Pericenter distance of the vacuum trajectory defined by position and velocity at the beginning phases 1 and 5. (L)
r_s	(input quantity) Radial distance of vehicle from the center of the re-entry planet defining the beginning and end of phase 4. (L)
$\dot{r}$	Current value of radial speed of vehicle. (LT^{-1})
$\dot{r}_{pc}$	Used to test radial velocity for switching to phases 2 or 6 if TRACC = 1. The value of $\dot{r}_{pc}$ is determined by the input quantity C_{vpc} ($\dot{r}_{pc} = C_{vpc} \sqrt{g_o R}$). (LT^{-1})

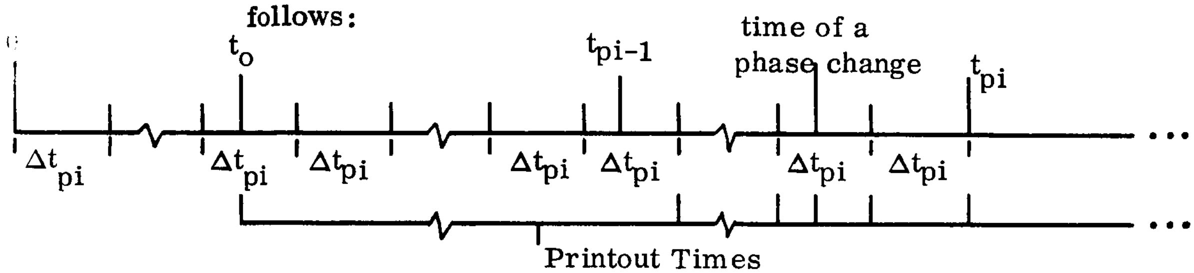
r_o, λ_o, μ_o	(input quantities) Initial position. Used only when TRINP = 0 and constitutes the initial position of the vehicle in spherical coordinates where r_o, λ_o, μ_o refer, respectively, to radial distance, latitude, and longitude. (L, R, R)
r, λ, μ	Current values of r_o, λ_o, μ_o. (L, R, R)
R	(input quantity) Sea level radius of re-entry planet. (L)
R_N	(input quantity) Radius of curvature of the vehicle at the heat stagnation point. (L)
$\underline{R}_O, \underline{R}_{Oo}$	See $\underline{P}_I$, $\underline{Y}_A$, $\underline{R}_O$ and $\underline{P}_{Io}$, $\underline{Y}_{Ao}$, $\underline{R}_{Oo}$, respectively.
S	(input quantity) Aerodynamic area. The cross sectional aerodynamic area of the vehicle used to compute the aerodynamic forces.
t	Current value of time (used in equations). (T)
t_i	Current value of time (used in computer). (T)
t_{i+1}	Value of time at the next cycle through the dynamic blocks. (T)
t_o	(input quantity) Initial time. Value of time at which program begins. (T)
t_1	Time at which the first supercircular phase beings (phase 1). (T)
t_2	Time at which the first supercircular phase ends and the first constant altitude phase (phase 2) begins. (T)
t_3	(input quantity) Time at which the first constant altitude phase ends and the first skipout control phase (phase 3) begins. (T)
t'_3	(input quantity) Time at which the first skipout control phase ends and the second skipout control phase (phase 3 modified) begins. (T)
t_4	Time at which skipout control ends and the free-fall phase (phase 4) begins. (T)
t_5	Time at which the free-fall phase ends and the second supercircular phase (phase 5) begins. (T)
t_6	Time at which the second supercircular phase ends and the second constant altitude control phase (phase 6) begins. (T)

t_7 — Time at which the second constant altitude phase ends and the subcircular phase (phase 7) begins. (T)

t_8 — Time at which the subcircular phase ends (the program ends here also). (T)

t_{END} — (input quantity) End time. The program will end when $t_i \geq t_{END}$. (T)

t_{pi} — (input quantity) $(i = 1, 2, \ldots, 10)$ Print interval time end points. These times define the interval over which the Δt_{pi} are used. The Δt_{pi} are the lengths of time separating each printout. The printout is set up as follows:



Print times in the region $t_{pi-1} < t \leq t_{pi}$ are equally spaced with an interval of Δt_{pi} starting at t_{pi} and proceeding backwards in time to the first point of the interval where $t > t_{pi-1}$. The Δt_{pi} must be an integer multiple of t_{pi}. Exceptions to this are at t_o and the time that a change of phase occurs. Here a printout always occurs. (T)

t_{Gi} — (input quantities) $(i = 1, 2, \ldots, 10)$ Nominal control calculation interval end points. The function and operation of these times is the same as that of the t_{pi} except that the t_{Gi} times refer to intervals of nominal control calculation rather than times of printout. This list is independent of the t_{pi} list. (T)

T_c — (input quantity) Time at the beginning of the constant altitude control phases (2 and 5). This number must be input only if the program is started in either phase 2 or phase 5. (T)

T'_c — (input quantity) Time at the beginning of either of the skipout control phases (phase 3 or phase 3 modified). This number must be input only if the program is started in either of the skipout control phases. (T)

If $t'_3 \leq t < t'_3$ then $T'_c = t_3$

If $t'_3 \leq t < t_4$ then $T'_c = t'_3$

TPLUS — The minimum value of future time at which at least one of the following conditions is met. (T)

1. Nominal control calculation
2. Print and/or store data
3. Change phase
4. End run

(TPLUS is the time to which the program integrates - Block I.4.) (T)

$\underline{U}_p$ — Unit vector ($\underline{i}$, $\underline{j}$, $\underline{k}$ coordinates) perpendicular to the current orbit plane.

$\underline{U}_{po}$ — Unit vector ($\underline{i}$, $\underline{j}$, $\underline{k}$ coordinates) perpendicular to the initial orbit plane. The direction of $\underline{U}_p$ at $t = t_o$.

$\underline{U}_r$ — Unit vector ($\underline{i}$, $\underline{j}$, $\underline{k}$ coordinates) in the direction of the current position vector of the vehicle.

$\underline{U}_u$ — Unit vector ($\underline{i}$, $\underline{j}$, $\underline{k}$ coordinates) in the orbit plane perpendicular to the current velocity vector.

$\underline{U}_v$ — Unit vector ($\underline{i}$, $\underline{j}$, $\underline{k}$ coordinates) in the direction of the current velocity vector.

$\underline{V}_a$ — Velocity ($\underline{i}$, $\underline{j}$, $\underline{k}$ coordinates) at the apocenter calculated at the beginning of phase 4. (LT^{-1})

V_a — Magnitude of $\underline{V}_a$. (LT^{-1})

V_o, γ_o, A_o — (input quantities) Initial velocity in spherical coordinates. Input only if TRINP = 0. The coordinates are respectively initial speed, initial flight path angle, and initial azimuth of the vehicle. (LT^{-1}, R, R)

V, γ, A — Current values of V_o, γ_o, and A_o. (LT^{-1}, R, R)

$\underline{V}$ — Velocity vector ($\underline{i}$, $\underline{j}$, $\underline{k}$ coordinates). (LT^{-1})

$\underline{V}_t$ — Velocity vector ($\underline{i}_t$, $\underline{j}_t$, $\underline{k}_t$ coordinates set up at $t = t_o$). (LT^{-1})

V_{IN} — (input quantity) If the program is in phase 6 and TRSBCL = 1, phase 7 will begin at $V = V_{IN}$. Also, if the program is in phase 3 (or 3 modified) and $\dot{r} \le 0$ and $V \le V_{IN}$, the program ends. (LT^{-1})

V_{END} — (input quantity) When $V \le V_{END}$ in phase 7, the program ends. (LT^{-1})

X, Y, Z	Current position components of the vehicle. The direction of these magnitudes is along the $\underline{i}$, $\underline{j}$, $\underline{k}$ unit vectors, respectively. (L, L, L)
$\dot{X}, \dot{Y}, \dot{Z}$	Current velocity components of the vehicle ($\underline{i}$, $\underline{j}$, $\underline{k}$ coordinate system). (LT^{-1}, LT^{-1}, LT^{-1})
$\ddot{X}, \ddot{Y}, \ddot{Z}$	Acceleration components of the vehicle ($\underline{i}$, $\underline{j}$, $\underline{k}$ coordinate system). (LT^{-2}, LT^{-2}, LT^{-2})
X_o, Y_o, Z_o	(input quantities) Initial position components (at $t = t_o$) of vehicle in the $\underline{i}$, $\underline{j}$, $\underline{k}$ coordinate system. Used only if TRINP = 1. (L, L, L)
$\dot{X}_o, \dot{Y}_o, \dot{Z}_o$	(input quantities) Initial velocity components (at $t = t_o$) of vehicle in the $\underline{i}$, $\underline{j}$, $\underline{k}$ coordinate system. Used only if TRINP = 1. (LT^{-1}, LT^{-1}, LT^{-1})
X_a, Y_a, Z_a	Position components of vehicle at apocenter. This position is calculated at the beginning of phase 4 and represents the maximum distance the vehicle will achieve from the center of the re-entry planet ($\underline{i}$, $\underline{j}$, $\underline{k}$ coordinates). (L, L, L)
$\dot{X}_a, \dot{Y}_a, \dot{Z}_a$	Velocity components of vehicle at apocenter. This velocity is calculated at the beginning of phase 4 and represents the velocity of the vehicle at its maximum distance from the planet ($\underline{i}$, $\underline{j}$, $\underline{k}$ coordinates). (LT^{-1}, LT^{-1}, LT^{-1})
X_t, Y_t, Z_t	Current position components of the vehicle in $\underline{i}_t$, $\underline{j}_t$, $\underline{k}_t$ coordinate system. (L, L, L)
$\dot{X}_t, \dot{Y}_t, \dot{Z}_t$	Current velocity components of the vehicle in the $\underline{i}_t$, $\underline{j}_t$, $\underline{k}_t$ coordinate system. (LT^{-1}, LT^{-1}, LT^{-1})
$\underline{Y}_A$, $\underline{Y}_{Ao}$	See $\underline{P}_I$, $\underline{Y}_A$, $\underline{R}_O$ and $\underline{P}_{Io}$, $\underline{Y}_{Ao}$, $\underline{R}_{Oo}$ respectively.
α	Angle of attack. This is the angle between R_O (the roll axis fixed in the vehicle) and the velocity vector ($\underline{V}$) and is assumed to remain constant throughout the flight. α is equal to α' during phase 1, 2, and 3; α'' during phase 4, 5, 6, and 7. (R)
α'	(input quantity) The angle of attack (α) has the value α' during phases 1, 2, and 3. (R)
α''	(input quantity) The angle of attack (α) has the value α'' during phases 4, 5, 6, and 7. (R)

$\alpha_1, \alpha_2, \alpha_3$ — Body Euler angles. These angles define the present orientation of the body-fixed axes ($\underline{P}_I$, $\underline{Y}_A$, $\underline{R}_O$) with respect to the position of the reference body-fixed axes ($\underline{P}_{Io}$, $\underline{Y}_{Ao}$, $\underline{R}_{Oo}$). The transformation is shown in Block I. 5. (R, R, R)

$\alpha_{1o}, \alpha_{2o}, \alpha_{3o}$ — (input quantities) Initial values (at $t = t_o$) of α_1, α_2, α_3. The transformation is shown in Block B. 4. (R, R, R)

β — Angle of the velocity vector projected onto the local horizontal plane measured clockwise from the plane defined by $\underline{r}$ and $\underline{k}_t$. (R)

β' — (input quantity) Re-entry planet atmospheric density decay factor. (L^{-1})

β_{φ} — (input quantity) Limit on the roll angle rate. Regardless of the commanded roll angle, the vehicle will not exceed a roll rate of β_{φ}. (T^{-1})

$\Delta\varphi_c$ — A change in commanded roll angle of the vehicle designed to null the deviations in r and $\dot{r}$ from desired values during the constant altitude phases (2 and 6). (R)

Δt_{pi} — (input quantities) (i = 1, . . . , 10) Ten values of time which specify how often a printout takes place. The length of time over which each Δt_{pi} is used is specified by t_{pi}. See t_{pi} for a more detailed explanation.

Δt_{Gi} — (input quantities) (i = 1, . . . , 10) Ten values of time which specify how often the nominal control block is entered. Each Δt_{Gi} is used over the interval of time specified by t_{Gi}. See t_{Gi} for a more detailed explanation. (T)

δt — Integration step size used by the integration routine. (T)

δt_1 — (input quantity) δt has the value δt_1 for all phases except phase 4. (T)

δt_2 — (input quantity) δt has the value δt_2 for phase 4. (T)

ϵ — The value of time, t, obtained within the integration routine must agree within ϵ to the time established as an integration routine exit time. (T)

ϵ_1 — (input quantity) ϵ has the value ϵ_1 during all phases except phase 4. (T)

ϵ_2 — (input quantity) ϵ has the value ϵ_2 during phase 4. (T)

ϵ_S	(input quantity) Out-of-plane velocity test value. At the start of the program ($t = t_0$), an initial flight path plane is determined by the velocity vector and the center of the re-entry planet. As the vehicle proceeds in its re-entry, the sine of the angle between the velocity vector and this initial plane is compared to ϵ_S. When the magnitude of the sine of this angle exceeds ϵ_S, the sign of φ_C is changed. This has the effect of keeping the vehicle near the re-entry plane. (R)
γ	Flight path angle. Angle between the velocity vector and its projection on the local horizontal plane. (R)
γ_o	(input quantity) Input only if TRINP = 1. Initial value (at $t = t_o$) of γ. (R)
γ_{max}	(input quantity) Maximum value γ may have at the beginning of phase 4 without the program terminating. (R)
γ_{min}	(input quantity) Minimum value γ may have at the beginning of phase 4 without the program terminating. (R)
λ	Latitude of vehicle. Angle between the $\underline{i}\ \underline{j}$ plane and present position vector. (R)
λ_o	(input quantity) Initial latitude of vehicle. Input only if TRINP = 0. (R)
μ	Longitude of vehicle. Angle between the $\underline{i}\ \underline{k}$ plane and the projection of the position vector on the $\underline{i}\ \underline{j}$ plane. (R)
μ_o	(input quantity) Initial longitude of vehicle. Input only if TRINP = 0. (R)
$\underline{\omega}$	Angular rate of vehicle. Expressed in terms of ω_{PI}, ω_{YA}, ω_{RO}, the components of $\underline{\omega}$ along the pitch, yaw, and roll axes of the vehicle, respectively. (T^{-1})
ω	Magnitude of $\underline{\omega}$. (T^{-1})
ω_{PI}, ω_{YA}, ω_{RO}	Components of angular rate (ω) along the pitch, yaw, and roll axes of the vehicle, respectively. (T^{-1}, T^{-1}, T^{-1})
$\omega_{\varphi i-1}$	Value used by program in the calculation of φ_C if $\lvert\omega_{\varphi i-1}\rvert \leq \beta_{\varphi}$. If $\lvert\omega_{\varphi i-1}\rvert > \beta_{\varphi}$, $\omega_{\varphi i-1}$ is replaced by β_{φ}. (T^{-1})

φ, φ_i	Current value of the roll angle. φ is the angle between the vertical plane through the velocity vector ($\underline{V}$) and the normal force ($\underline{N}$). (R)
φ_{i-1}	The value of φ_i resulting from the previous nominal control calculation. (R)
φ_o	(input quantity) Initial roll angle (φ at $t = t_o$). (R)
φ_c	Commanded roll angle. (R)
φ_{c1}	The value of φ_c during phases 1 and 5 (supercircular constant roll angle control phases). (R)
φ_{c3}	(input quantity) The value of φ_c during phase 7 (subcircular constant roll angle control phase). (R)
φ_{11}	(input quantity) The value of φ_{c1} during phase 1 (first supercircular constant roll angle control phase). (R)
φ_{21}	(input quantity) The value of φ_{c1} during phase 5 (second supercircular constant roll angle control phase). (R)
ϕ	An angle measured in the $\underline{i}_t$ $\underline{j}_t$ plane from $\underline{j}$ to the plane formed by $\underline{r}$ and $\underline{k}_t$. (R)
ρ	Atmospheric density of re-entry planet. (ML^{-3})
ρ_o	(input quantity) Sea level atmospheric density of re-entry planet. (ML^{-3})
θ	Range angle plus 90°. An angle measured in the $\underline{r}$ $\underline{k}_t$ plane from $\underline{k}_t$ to $\underline{r}$. (R)
τ	Period of constant altitude roll angle. $\tau = \tau_1$ in phase 2 and $\tau = \tau_2$ in phase 6. Used only if TROPGN = 1. (T)
τ_1, τ_2	(input quantities) Constant roll angle control periods. Input only if TROPGN = 1. The natural period of the constant altitude roll angle control will be τ_1 and τ_2 for phases 2 and 6, respectively, if TROPGN = 1. (T, T)
$\tau'(a)$	The interval of time that a pilot can remain usefully conscious at a given acceleration (a) level. τ' is a function of a. (T)

ζ Damping ratio of constant altitude roll angle. $\zeta = \zeta_1$ in phase 2 and $\zeta = \zeta_2$ in phase 6. Input only if TROPGN = 1.

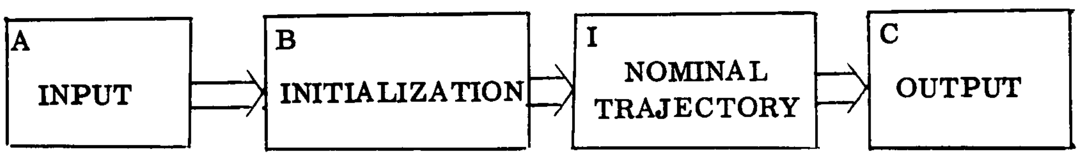
ζ_1, ζ_2 (input quantities) Damping ratios for constant altitude roll angle control. Input only if TROPGN = 1. The damping ratio of the constant altitude roll angle control will be ζ_1 and ζ_2 for phases 2 and 6, respectively, if TROPGN = 1.

3.2 BASIC ORGANIZATION OF PROGRAM

The basic structure of the program is summarized in the flow chart below. It constitutes, according to preceding definitions, the Level I flow chart and consists of two different classes of blocks. Those which define the basic computational cycles of the program (Roman numerals), and those necessary to start the program in a prescribed way or define the required output (Arabic letters A, B, C).

The INPUT block represents a summary of the quantities that an engineer must input. No computations are contained within this block. In the INITIALIZATION block, computations that must be performed once during a specific simulation run and/or logical decisions that must be made for proper operation within the basic computational cycle are accomplished. The OUTPUT block defines the quantities that are to be available for printout purposes and contains computations that are not required in the basic computational cycle.

The NOMINAL TRAJECTORY block consists of the equations and logic which are required to describe the path of the vehicle through the atmosphere.



Level I Flow Chart - Single-Pass/Skipout Nominal Re-entry Trajectory

3.3 INPUT, GENERAL INITIALIZATION, OUTPUT

3.3.1 Input - Block A

Input format

Flags

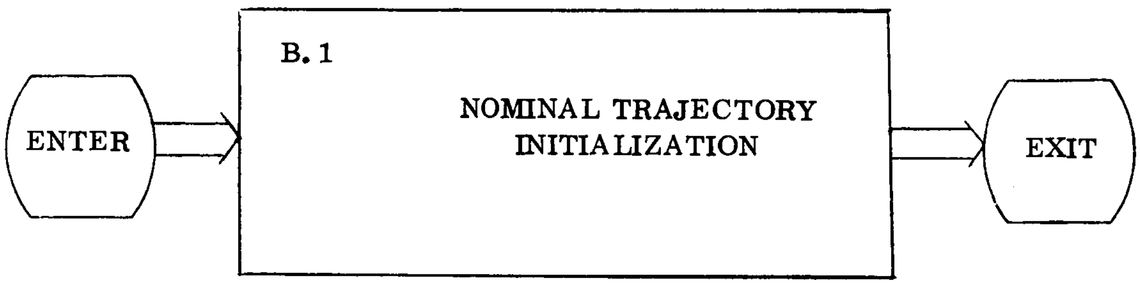
TRINP; TRPHSE; TRSBCL; TROPGN; TRACC

Constants

C_{apc}; C_{vpc}; C_{D_o}; C_2; C_4; C_{N_α}; C_3; C_5; C_{e1}; C_{e2}; C_H; E_i (i = 0, 1, 2, 3, 4); F_{1i} (i = 0, 1, 2): F_{2i} (i = 0, 1, 2); g_e; g_o; G_{max}; k_H (K_{11}, K_{21} or ζ_1, τ_1); (K_{21}, K_{22} or ζ_2, τ_2); K_{13}; K_{23}; K_ϖ; M; m; n; p_H; $q_1 q_2$; (r_o, μ_o, λ_o or X_o, Y_o, Z_o); r_c; r_m; r_{ma}; r_s; R; R_N; S; t_o; t_{END}; t_3; t_3'; t_{Gi}, t_{pi} (i = 1, 2, . . . , 10); T_c; T_c'; (V_o, γ_o, A_o or $\dot{X}_o$, $\dot{Y}_o$, $\dot{Z}_o$); V_{IN}; V_{END}; α'; α''; α_{io} (i = 1, 2, 3); β'; β_ϖ; δt_1; δt_2; Δt_{Gi}, Δt_{pi} (i = 1, . . . , 10); ϵ_1; ϵ_2; ϵ_s; γ_{min}; γ_{max}; ϖ_o; ϖ_{11}; ϖ_{21}; ϖ_{c3}; ρ_o

3.3.2 General Inititalization - Block B

3.3.2.1 Initialization - Block B



Level II Flow Chart - Initialization

The detailed equations and flow charts for this block appear on the following pages.

3.3.2.2 Detailed Flow Charts and Equations

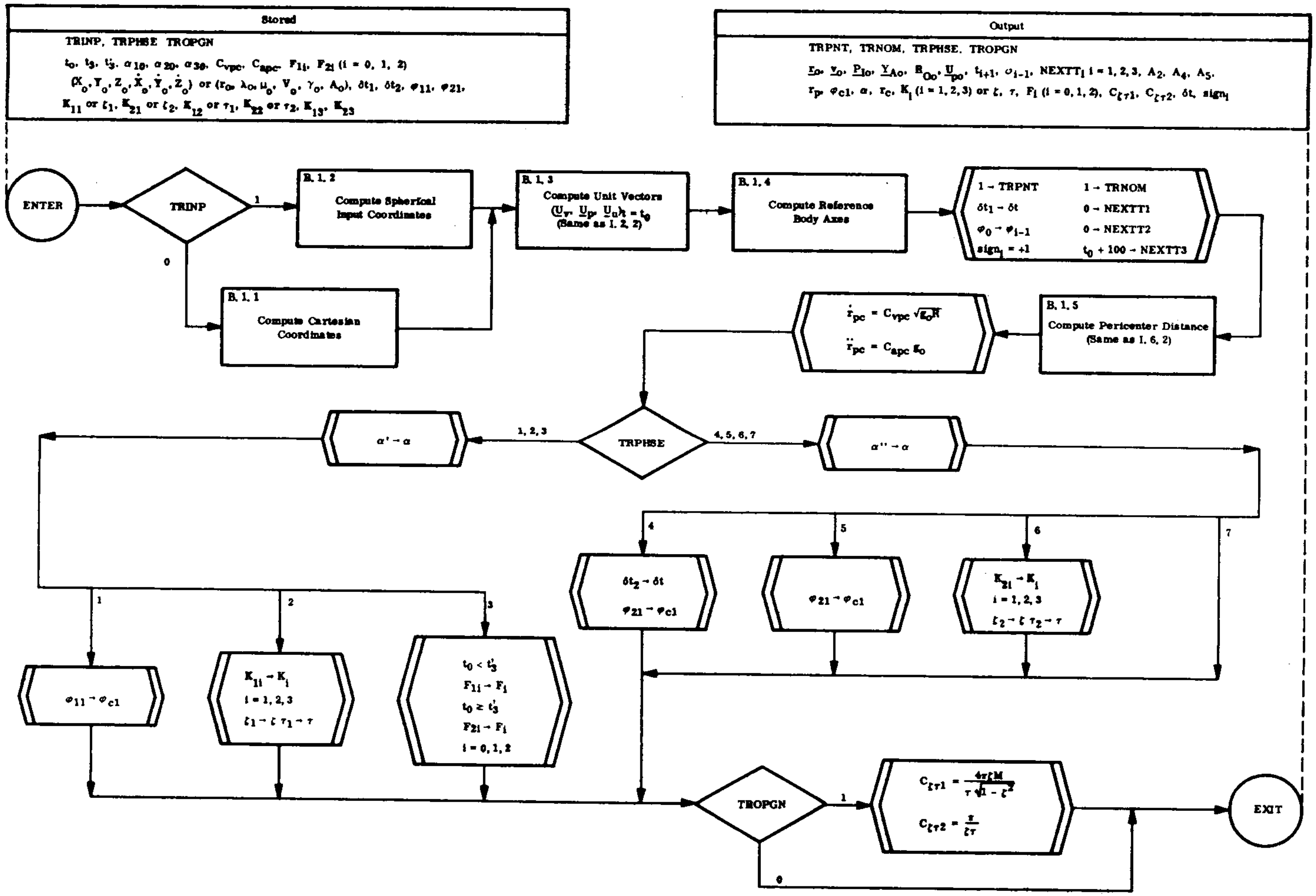


Figure 3. 3. 2. 2. 1 - Nominal Initialization Block B. 1

Block B. 1. 1 Compute Cartesian Coordinates

INPUT: r_o, λ_o, μ_o, V_o, γ_o, A_o

OUTPUT: X_o, Y_o, Z_o, $\dot{X}_o$, $\dot{Y}_o$, $\dot{Z}_o$

$$X_o = r_o \cos \lambda_o \cos \mu_o$$

$$Y_o = r_o \cos \lambda_o \sin \mu_o$$

$$Z_o = r_o \sin \lambda_o$$

$$\dot{X}_o = V_o(- \cos \gamma_o \cos A_o \sin \lambda_o \cos \mu_o - \cos \gamma_o \sin A_o \sin \mu_o + \sin \gamma_o \cos \lambda_o \cos \mu_o)$$

$$\dot{Y}_o = V_o(- \cos \gamma_o \cos A_o \sin \lambda_o \sin \mu_o + \cos \gamma_o \sin A_o \cos \mu_o + \sin \gamma_o \cos \lambda_o \sin \mu_o)$$

$$\dot{Z}_o = V_o (\cos \gamma_o \cos A_o \cos \lambda_o + \sin \gamma_o \sin \lambda_o)$$

Block B. 1. 2 Compute Spherical Input Coordinates

INPUT: $X_o, Y_o, Z_o, \dot{X}_o, \dot{Y}_o, \dot{Z}_o$

OUTPUT: $r_o, \lambda_o, \mu_o, V_o, \gamma_o, A_o$

1. $$r_o = +\sqrt{X_o^2 + Y_o^2 + Z_o^2}$$

2. $$\mu_o = \tan^{-1}\left[\frac{Y_o}{X_o}\right] \qquad -\pi < \mu_o \leq \pi$$

3. $$\lambda_o = \sin^{-1}\left[\frac{Z_o}{r_o}\right] \qquad -\frac{\pi}{2} \leq \lambda_o \leq \frac{\pi}{2}$$

4. $$V_o = +\sqrt{\dot{X}_o^2 + \dot{Y}_o^2 + \dot{Z}_o^2}$$

5. $$\gamma_o = \sin^{-1}\left[\frac{X_o\dot{X}_o + Y_o\dot{Y}_o + Z_o\dot{Z}_o}{r_o V_o}\right] \qquad -\frac{\pi}{2} \leq \gamma_o \leq \frac{\pi}{2}$$

6. $$A_o = \tan^{-1}\left[\frac{-\sin\mu_o\dot{X}_o + \cos\mu_o\dot{Y}_o}{-\sin\gamma_o\cos\mu_o\dot{X}_o - \sin\lambda_o\sin\mu_o\dot{Y}_o + \cos\lambda_o\dot{Z}_o}\right]$$

$$-\pi < A_o \leq \pi$$

Block B. 1. 3 Compute Unit Vectors $(\underline{U}_v, \underline{U}_p, \underline{U}_u)_{t = t_o}$

This block is the same as I. 2. 2 (Compute Aerodynamic Forces) even though the only quantities needed are $\underline{U}_v$, $\underline{U}_p$, $\underline{U}_u$.

INPUT: $\underline{r}_o, \underline{v}_o, \rho_o, \beta', R, S, C_{D_o}, C_2, C_4, C_{N_\alpha}, C_3, C_5, \alpha, \varphi_o$

OUTPUT: $(\underline{U}_v, \underline{U}_r, \underline{U}_p, \underline{D}, \underline{N}, \dot{r})_{t = t_o}$

1. $V = +\sqrt{\dot{X}^2 + \dot{Y}^2 + \dot{Z}^2}$
2. $\underline{U}_v = \dfrac{\underline{V}}{V}$
3. $r = +\sqrt{X^2 + Y^2 + Z^2}$
4. $\underline{U}_r = \dfrac{\underline{r}}{r}$
5. $\gamma = \sin^{-1} [\underline{U}_r \cdot \underline{U}_v]$
6. $\dot{r} = V \sin \gamma$
7. $\underline{U}_u = \dfrac{\underline{U}_r - \underline{U}_v \sin \gamma}{\cos \gamma}$
8. $\underline{U}_p = \underline{U}_u \times \underline{U}_v$
9. $\rho = \rho_o e^{-\beta' (r - R)}$
10. $C_D = C_{Do} + C_2 \alpha^2 + C_4 \alpha^4$
11. $C_N = C_{N\alpha} \alpha + C_3 \alpha^3 + C_5 \alpha^5$
12. $\underline{D} = - C_D \rho \dfrac{V^2 S}{2} \underline{U}_v$
13. $\underline{N} = C_N \rho \dfrac{V^2 S}{2} [\cos \varphi_i \underline{U}_u - \sin \varphi_i \underline{U}_p]$

NOTE: $(\underline{U}_p)_{t = t_o} = \underline{U}_{po}$, $\underline{U}_{po}$ is to be stored for later use.

Block B. 1. 4 Compute Reference Body Axes

INPUT: $(\underline{U}_v, \underline{U}_p, \underline{U}_u)_{t = t_o}$; α; α_{10}; α_{20}; α_{30}; φ_o; λ_o; μ_o; A_o

OUTPUT: $\underline{P}_{Io}$, $\underline{Y}_{Ao}$, $\underline{R}_{Oo}$, A_2, A_4, A_5

1. $$\underline{U}_m \triangleq U_{mx}\,\underline{i} + U_{my}\,\underline{j} + U_{mz}\,\underline{k}; \qquad m = v,\ p,\ u$$

2. $$A_2 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} 0 & \cos\varphi_o & \sin\varphi_o \\ 0 & -\sin\varphi_o & \cos\varphi_o \\ 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} U_{vx} & U_{vy} & U_{vz} \\ U_{px} & U_{py} & U_{pz} \\ U_{ux} & U_{uy} & U_{uz} \end{bmatrix}$$

3. $$A_3 = \begin{bmatrix} \cos\alpha_{10} & -\sin\alpha_{10} & 0 \\ \sin\alpha_{10} & \cos\alpha_{10} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\alpha_{20} & 0 & \sin\alpha_{20} \\ 0 & 1 & 0 \\ -\sin\alpha_{20} & 0 & \cos\alpha_{20} \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha_{30} & -\sin\alpha_{30} \\ 0 & \sin\alpha_{30} & \cos\alpha_{30} \end{bmatrix}$$

4. $$A_4 = A_3 A_2$$

5. $$\begin{bmatrix} \underline{P}_{Io} \\ \underline{Y}_{Ao} \\ \underline{R}_{Oo} \end{bmatrix} \triangleq A_4 \begin{bmatrix} \underline{i} \\ \underline{j} \\ \underline{k} \end{bmatrix}$$

6. $$A_5 = \begin{bmatrix} \sin A_o & \cos A_o & 0 \\ -\cos A_o & \sin A_o & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \sin\lambda_o & 0 & -\cos\lambda_o \\ 0 & 1 & 0 \\ \cos\lambda_o & 0 & \sin\lambda_o \end{bmatrix} \begin{bmatrix} \cos\mu_o & \sin\mu_o & 0 \\ -\sin\mu_o & \cos\mu_o & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & -1 & 0 \end{bmatrix}$$

Block B. 1. 5 Compute Pericenter Distance

This block is the same as I. 6. 2 (Compute Apocenter and Pericenter Distances) even though the only quantity needed is the pericenter distance.

INPUT: g_o, R, r_o, V_o, γ_o

OUTPUT: r_a, r_p

1. $\mu = g_o R^2$

2. $p = \dfrac{(r V \cos \gamma)^2}{\mu}$

3. $a_e = \dfrac{r \mu}{2\mu - r V^2}$

4. $e = + \sqrt{1 - p/a_e}$ limit p/a_e to be ≤ 1

5. Is $a < 0$?

   a. Yes: $r_a = 10^{20}$

   b. No: $r_a = a_e (1 + e)$

6. $r_p = a_e (1 - e)$

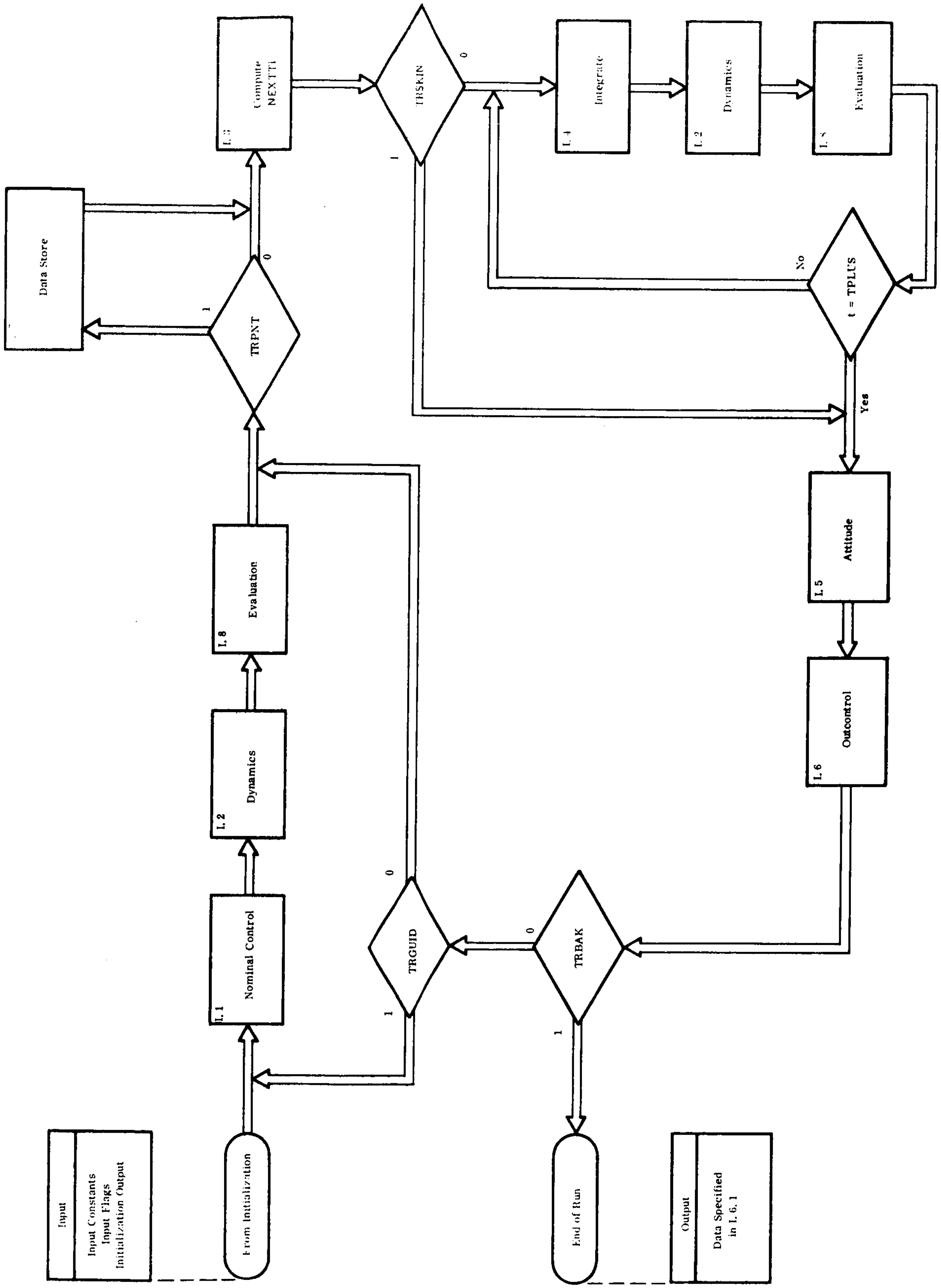
3.3.3 OUTPUT - BLOCK C

3.3.3.1 Output Format

t, φ_c, φ, q_s, Q, a', X, Y, Z, $\dot{X}$, $\dot{Y}$, $\dot{Z}$, r, θ, ϕ, V, γ, β, a_x, a_y, a_z, α_1, α_2, α_3, $\Delta\varphi_c$, $\ddot{r}$, Δr, ω_{PI}, ω_{YA}, ω_{RO}, h, $\dot{r}$, $|\underline{D}|$, $|\underline{N}|$, E_n, NEXTT3, r_a, r_p, X_a, Y_a, Z_a, $\dot{X}_a$, $\dot{Y}_a$, $\dot{Z}_a$

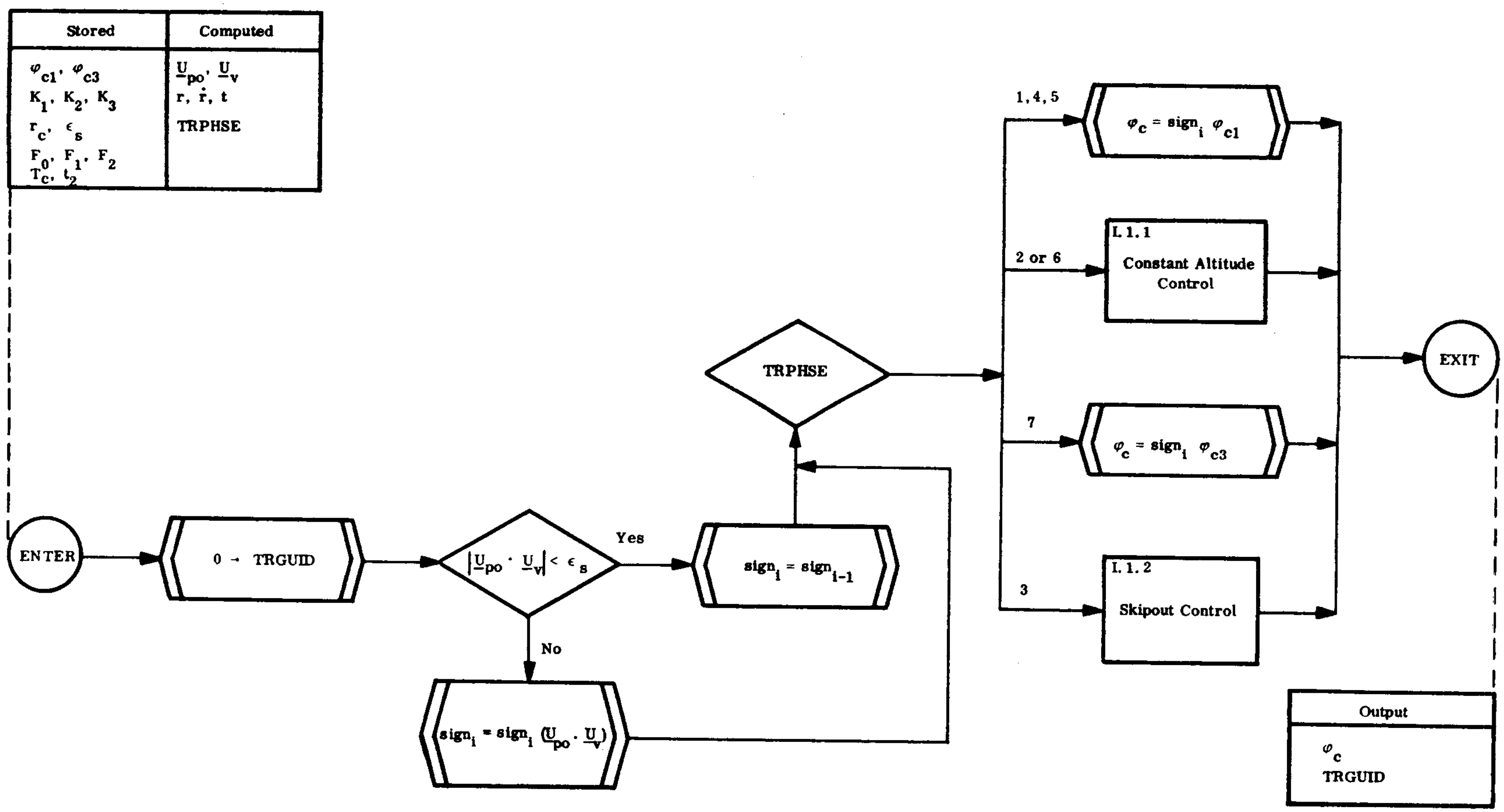
3.4 BASIC COMPUTATIONAL BLOCKS

3.4.1 TRAJECTORY BLOCK

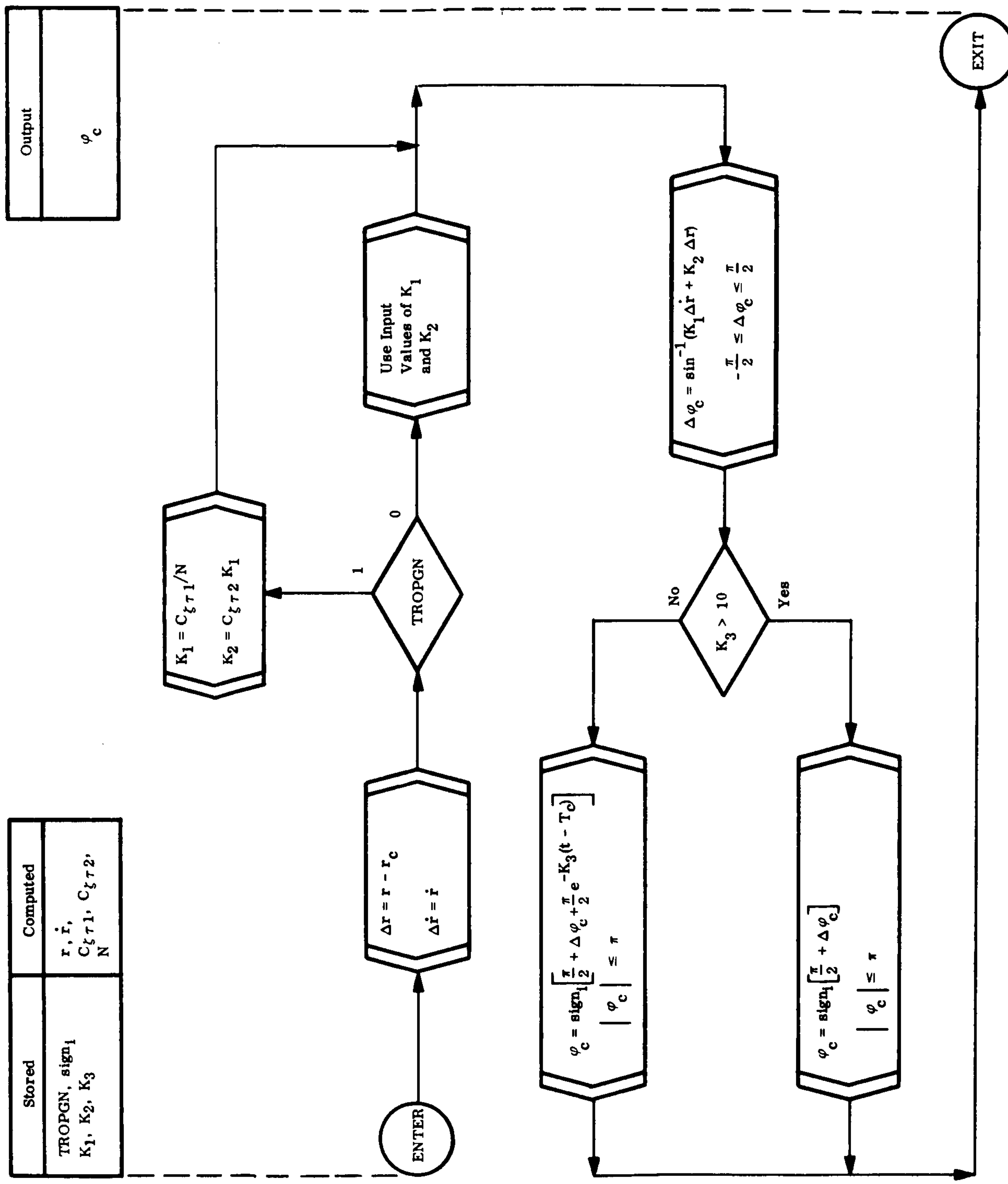


3.4.1.1 - Level II Flow Chart - Nominal Trajectory - Block I

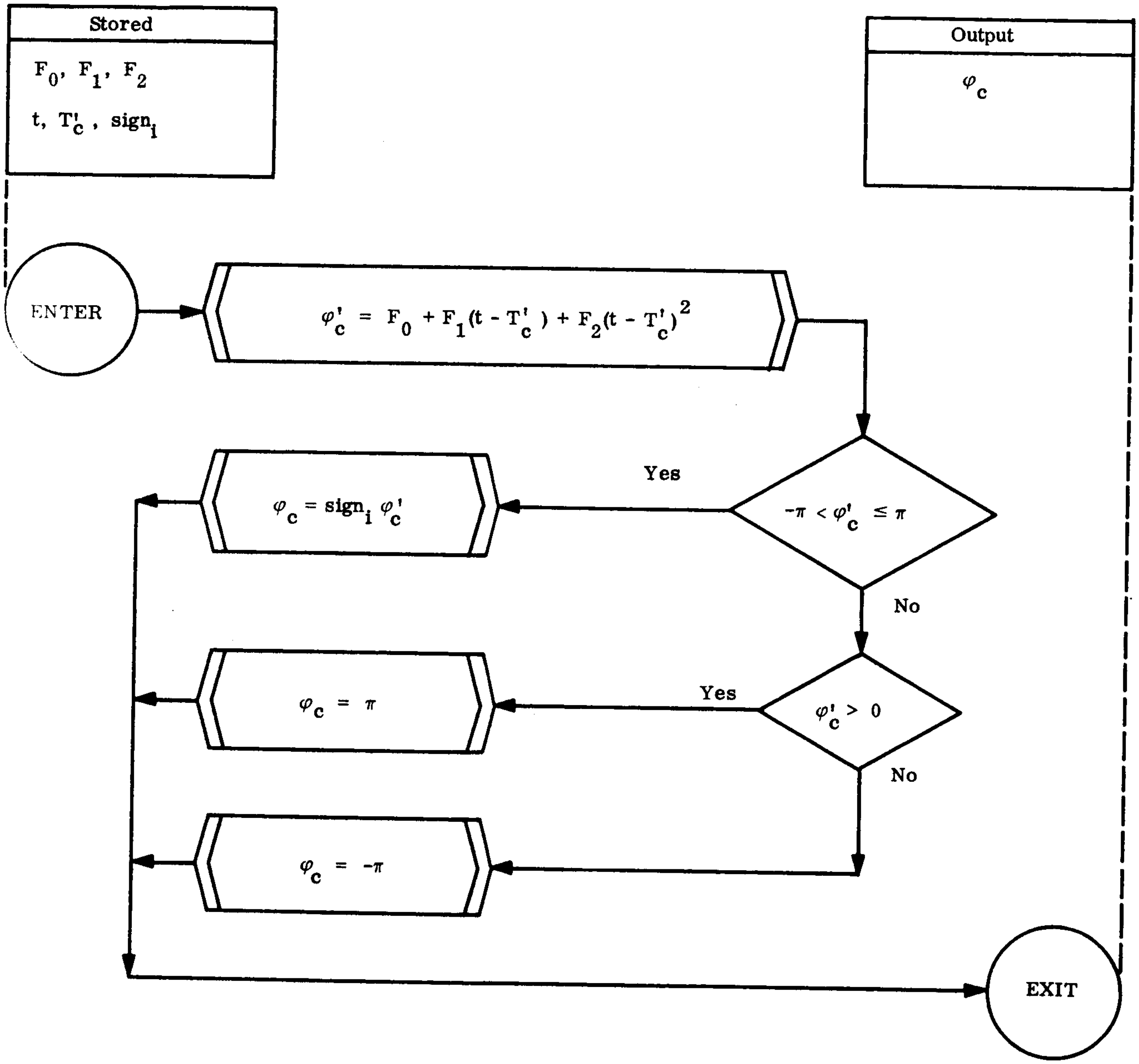
3.4.1.2 Detailed Flow Charts and Equations



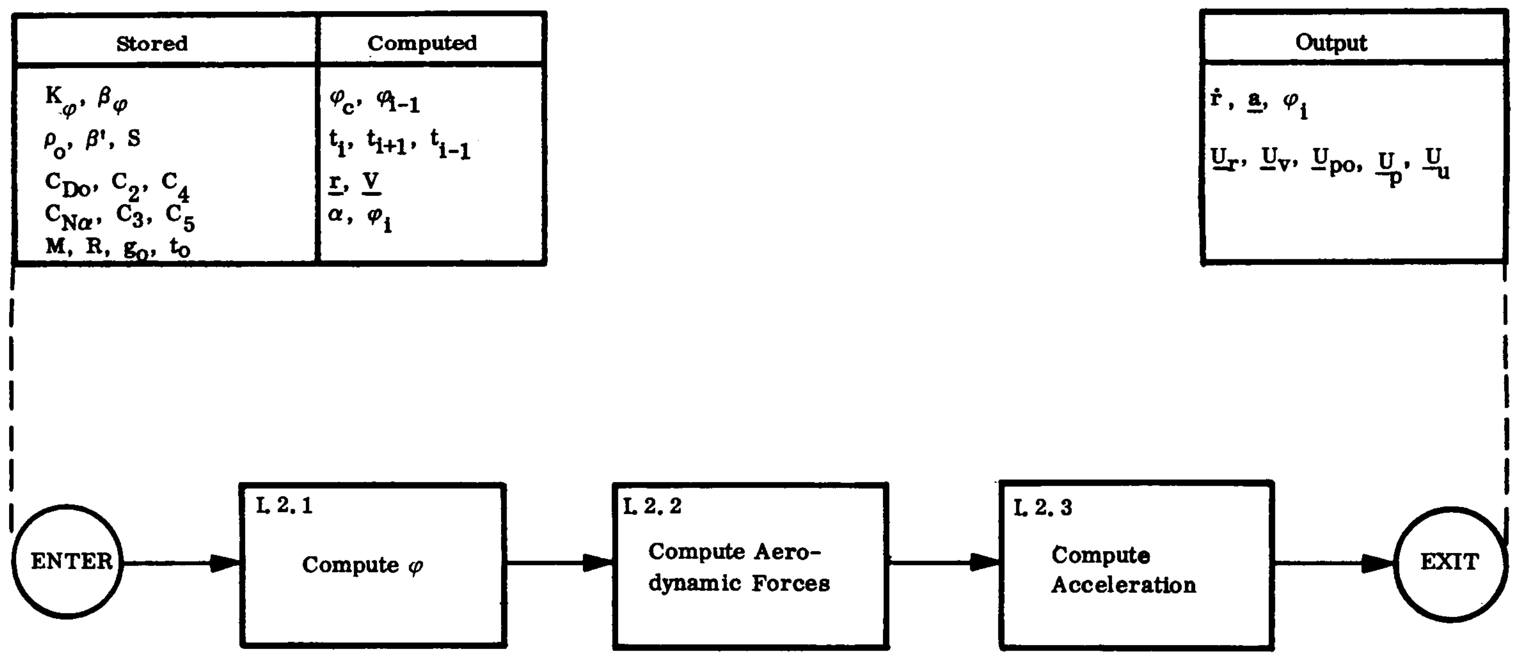
3.4.1.2.1 Nominal Control - Block I.1



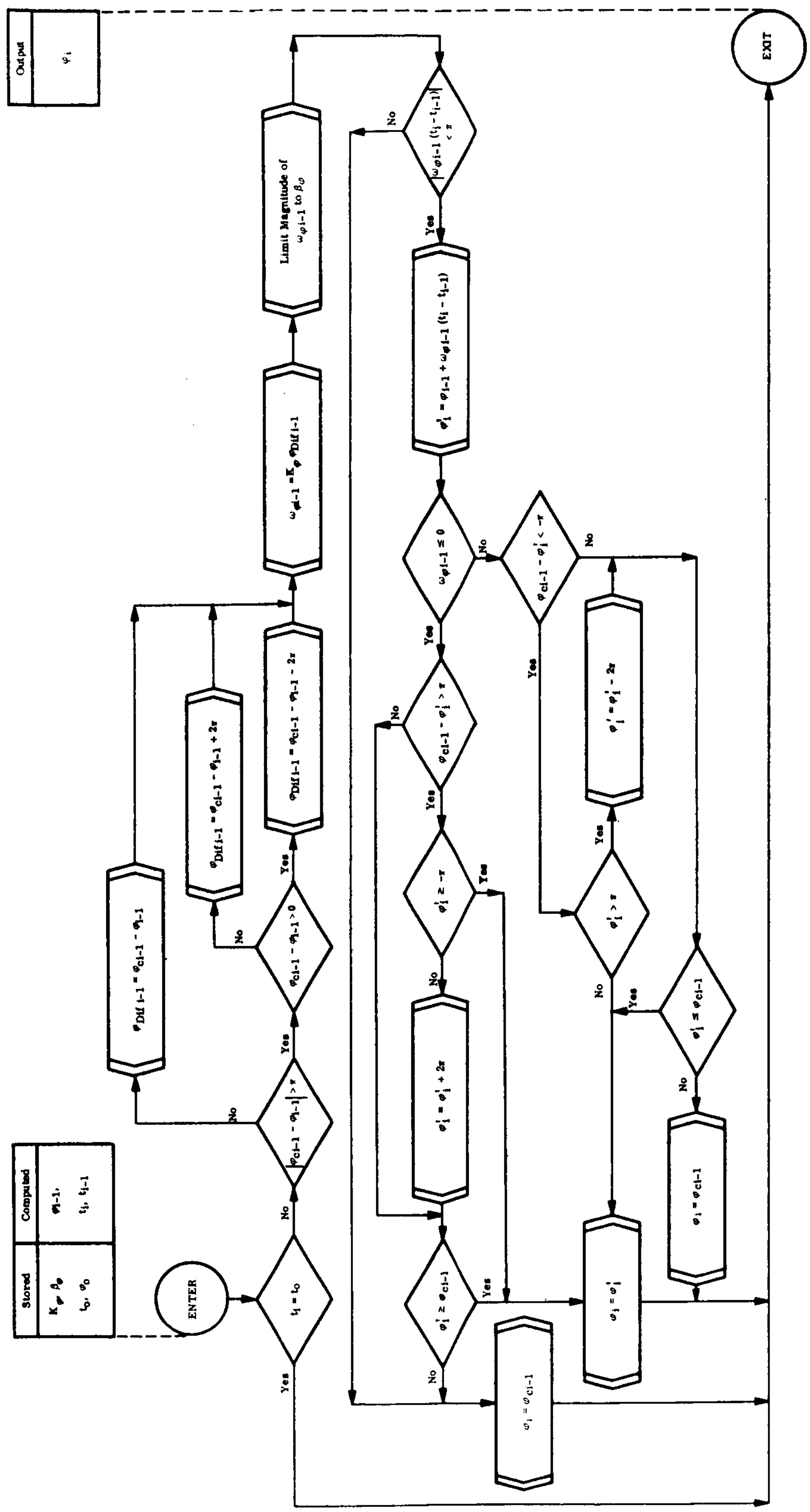
Block I.1.1 - Constant Altitude Control



Block I. 1. 2 Skipout Control



3.4.1.2.2 Dynamics - Block I.2



Block I. 2. 1 - Computer φ

Block I. 2. 2 Compute Aerodynamic Forces

INPUT: $\underline{r}$, $\underline{V}$, ρ_o, β', R, S, C_{Do}, C_2, C_4, $C_{N\alpha}$, C_3, C_5, α, φ_i

OUTPUT: $\underline{U}_v$, $\underline{U}_r$, $\underline{U}_{po}$, $\underline{D}$, $\underline{N}$, $\dot{r}$

1. $V = +\sqrt{\dot{X}^2 + \dot{Y}^2 + \dot{Z}^2}$

2. $\underline{U}_v = \dfrac{\underline{V}}{V}$

3. $r = +\sqrt{X^2 + Y^2 + Z^2}$

4. $\underline{U}_r = \dfrac{\underline{r}}{r}$

5. $\gamma = \sin^{-1} [\underline{U}_r \cdot \underline{U}_v]$

6. $\dot{r} = V \sin \gamma$

7. $\underline{U}_u = \dfrac{\underline{U}_r - \underline{U}_v \sin \gamma}{\cos \gamma}$

8. $\underline{U}_p = \underline{U}_u \times \underline{U}_v$

9. $\rho = \rho_o e^{-\beta' (r - R)}$

10. $C_D = C_{Do} + C_2 \alpha^2 + C_4 \alpha^4$

11. $C_N = C_{N\alpha} + C_3 \alpha^3 + C_5 \alpha^5$

12. $\underline{D} = - C_D \rho \dfrac{V^2 S}{2} \underline{U}_v$

13. $\underline{N} = C_N \rho \dfrac{V^2 S}{2} [\cos \varphi_i \underline{U}_u - \sin \varphi_i \underline{U}_p]$

Block I. 2. 3 Compute Acceleration

INPUT: $\underline{D}$, $\underline{N}$, M, R, g_o

OUTPUT: a_x, a_y, a_z, $\ddot{X}$, $\ddot{Y}$, $\ddot{Z}$, $\underline{a}$, $\underline{f}$

1. $a_x = (D_x + N_x)/M$

2. $a_y = (D_y + N_y)/M$

3. $a_z = (D_z + N_z)/M$

4. $g = g_o \left(\frac{R}{r}\right)^2$

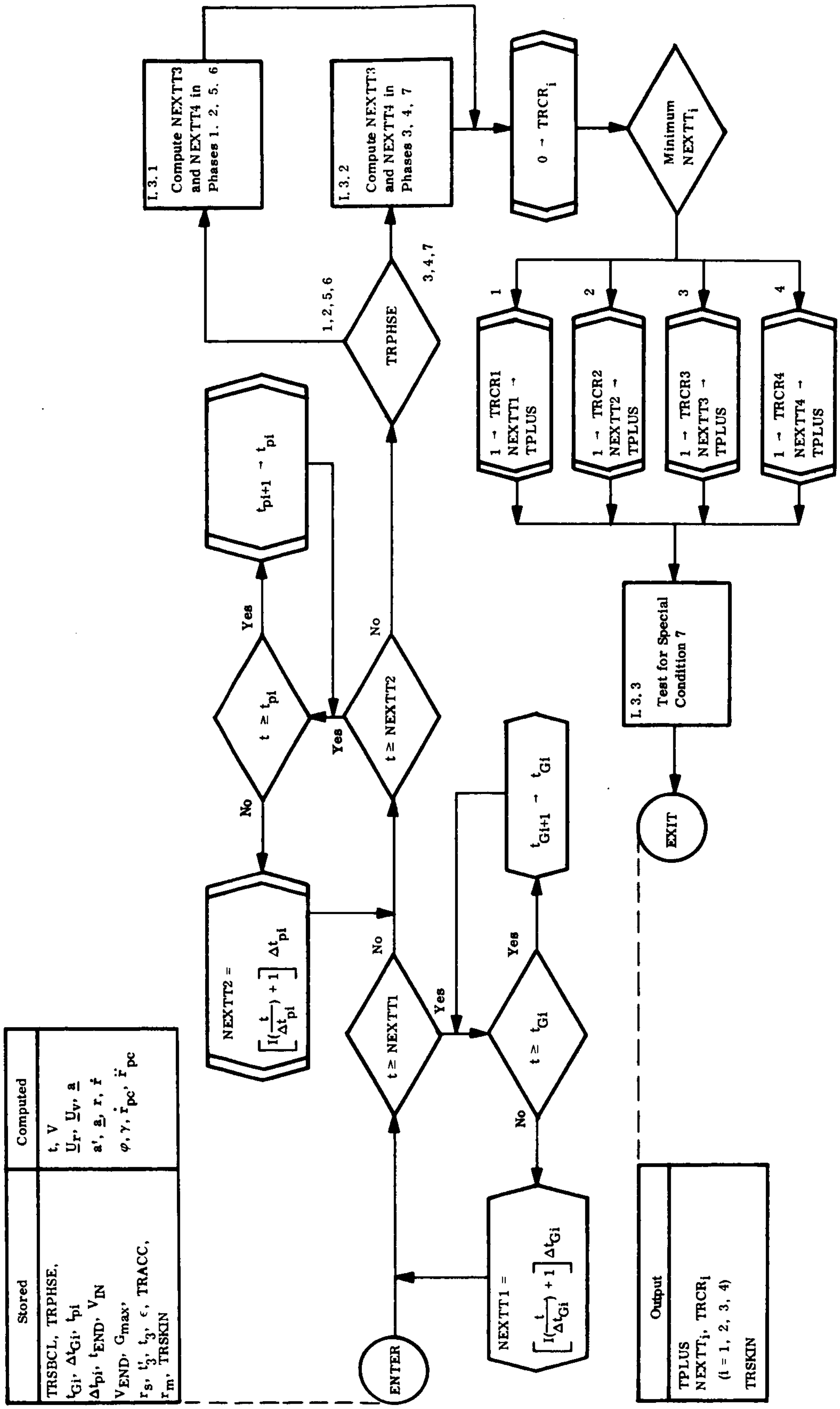
5. $\ddot{X} = a_x - g \frac{X}{r}$

6. $\ddot{Y} = a_y - g \frac{Y}{r}$

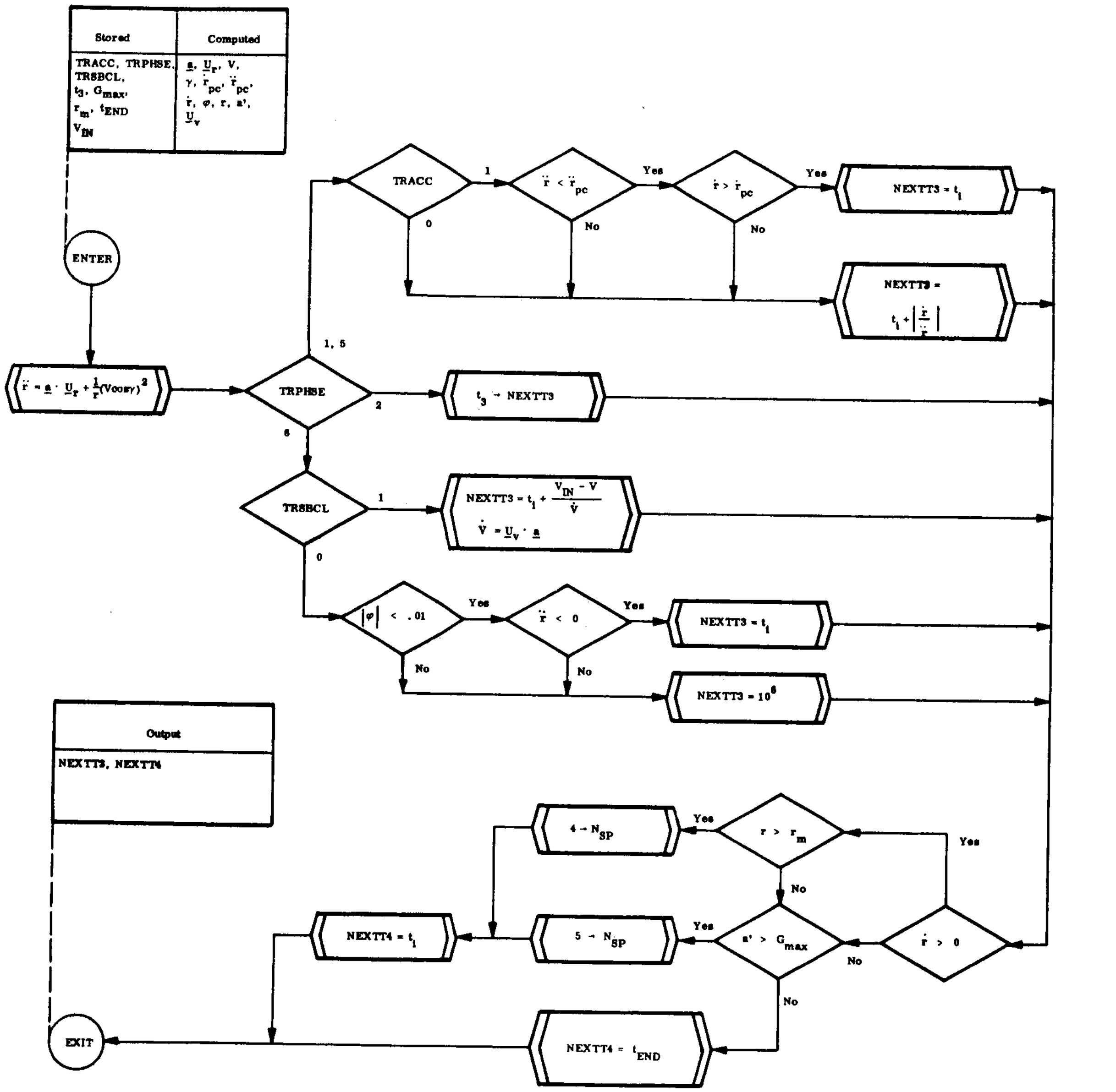
7. $\ddot{Z} = a_z - g \frac{Z}{r}$

8. $\underline{a} \triangleq \ddot{X}\,\underline{i} + \ddot{Y}\,\underline{j} + \ddot{Z}\,\underline{k}$

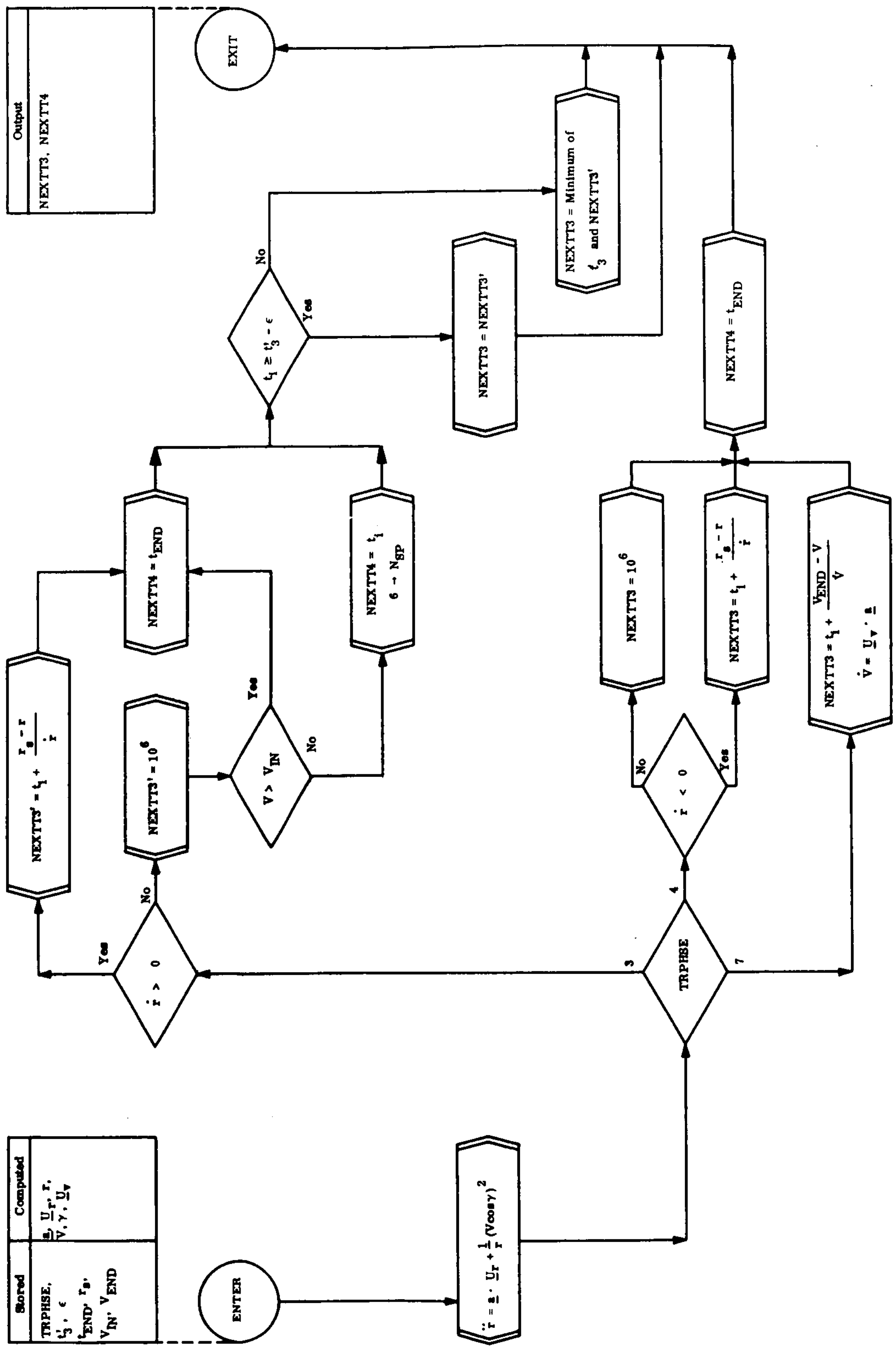
9. $\underline{f} \triangleq a_x \underline{i} + a_y \underline{j} + a_z \underline{k}$



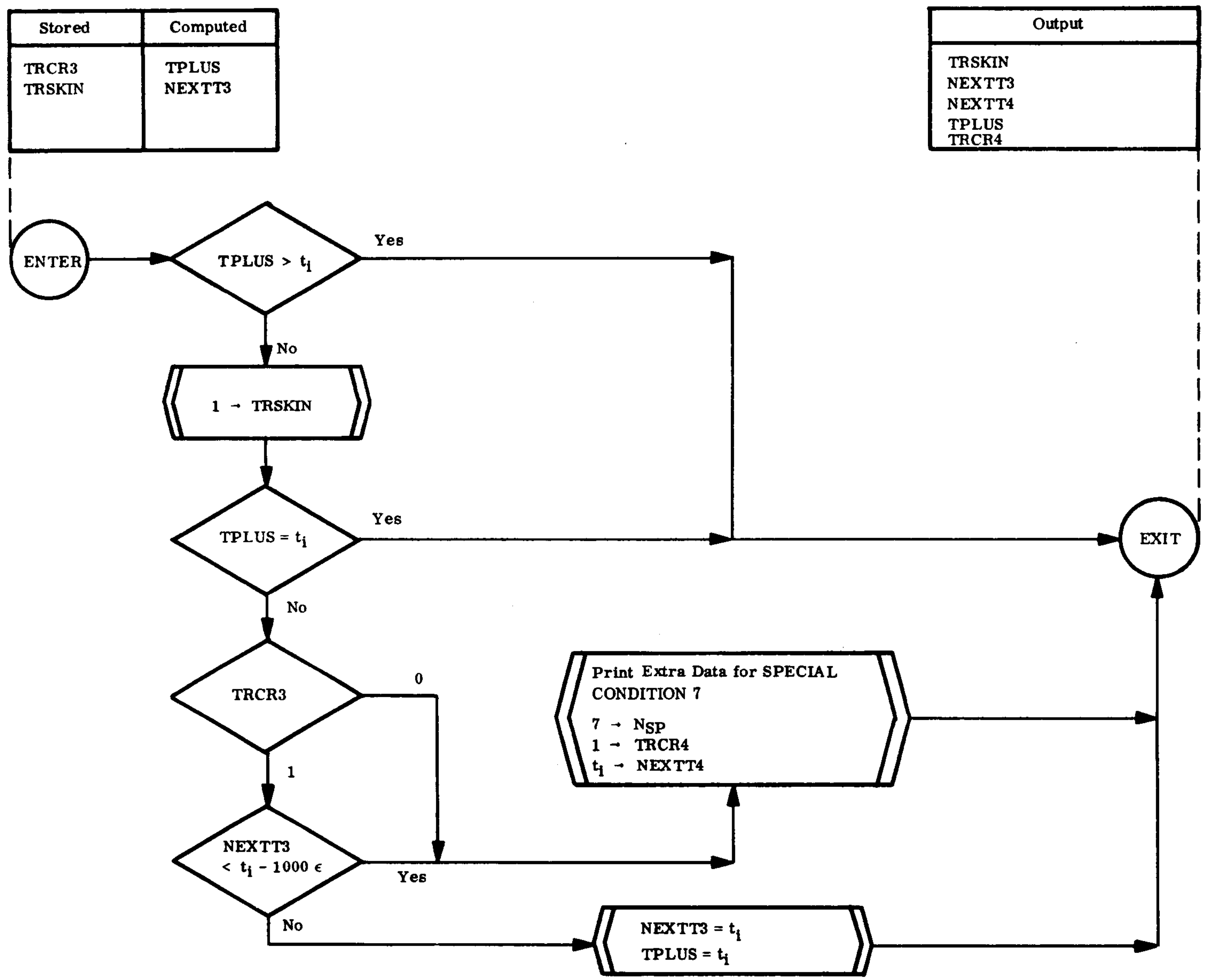
Block I. 3 - Compute NEXTTi



Block I. 3. 1 Compute NEXTT3 and NEXTT4 in Phases 1, 2, 5, and 6



Block I. 3. 2 - Compute NEXTT3 and NEXTT4 in Phases 3, 4, and 7



Block I. 3. 3 - Test for Special Condition 7

3.4.1.2.3 Integrate - Block I.4

INPUT: $\ddot{X}$, $\ddot{Y}$, $\ddot{Z}$, $\dot{X}$, $\dot{Y}$, $\dot{Z}$, q_s, $\dot{E}_n$

OUTPUT: X, Y, Z, $\dot{X}$, $\dot{Y}$, $\dot{Z}$, Q, E_n

The integration routine uses a fixed step size which is input to the program. The input specified above constitutes a partial set of the integrands which, along with the initial conditions, are required to determine the integrals listed in the output. Some of the integrands consist of the output of the integration routine (e.g., $\dot{X}$, $\dot{Y}$, $\dot{Z}$, is output from the integration routine and is used as input to obtain X, Y, Z). The integration equations used are the Gill equations listed below.

1. $$Y^{(1)}_{n+1} = Y_n + \frac{1}{2}\Delta t\,[Y'(t, Y_n)]$$

2. $$Y^{(2)}_{n+1} = Y^{(1)}_{n+1} + \left(\frac{2-\sqrt{2}}{2}\right)\Delta t\,[Y'(t+\frac{\Delta t}{2}, Y^{(1)}_{n+1}) - Y'(t, Y_n)]$$

3. $$Y^{(3)}_{n+1} = Y^{(2)}_{n+1} + \left(\frac{2-\sqrt{2}}{2}\right)\Delta t\,[Y'(t+\frac{\Delta t}{2}, Y^{(2)}_{n+1}] - \Delta t\,[Y'(t+\frac{\Delta t}{2}, Y^{(1)}_{n+1}] + \left(\frac{1-\sqrt{2}}{2}\right)\Delta t\,[Y'(t, Y_n)]$$

4. $$Y^{(4)}_{n+1} = Y^{(3)}_{n+1} + \frac{1}{6}\Delta t\,[Y'(t, Y_n) + Y'(t+\Delta t\, Y^{(3)}_{n+1})] - \left(\frac{2+\sqrt{2}}{2}\right)\Delta t\,[Y'(t+\frac{\Delta t}{2}, Y^{(2)}_{n+1})] + \left(\frac{1+\sqrt{2}}{2}\right)\Delta t\,[Y'(t+\frac{\Delta t}{2}, Y^{(1)}_{n+1})]$$

5. $$Y_{n+1} = Y^{(4)}_{n+1}$$

3.4.1.2.4 Attitude - Block I.5

INPUT: φ, α, $\underline{U}_v$, $\underline{U}_p$, $\underline{U}_u$, $\underline{P}_{Io}$, $\underline{Y}_{Ao}$, $\underline{R}_{Oo}$, t_i, t_{i-1}

OUTPUT: α_1, α_2, α_3, ω_{PI}, ω_{YA}, ω_{RO}

$$\begin{bmatrix} \underline{P}_I \\ \underline{Y}_A \\ \underline{R}_O \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} 0 & \cos\varphi & \sin\varphi \\ 0 & -\sin\varphi & \cos\varphi \\ 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} \underline{U}_v \\ \underline{U}_p \\ \underline{U}_u \end{bmatrix}$$

$$\alpha_1 = \tan^{-1}\left[\frac{\underline{P}_I \cdot \underline{Y}_{Ao}}{\underline{P}_I \cdot \underline{P}_{Io}}\right] \qquad -\pi < \alpha_1 \le \pi$$

$$\alpha_2 = \sin^{-1}\left[\underline{P}_I \cdot \underline{R}_{Oo}\right] \qquad -\frac{\pi}{2} \le \alpha_2 \le \frac{\pi}{2}$$

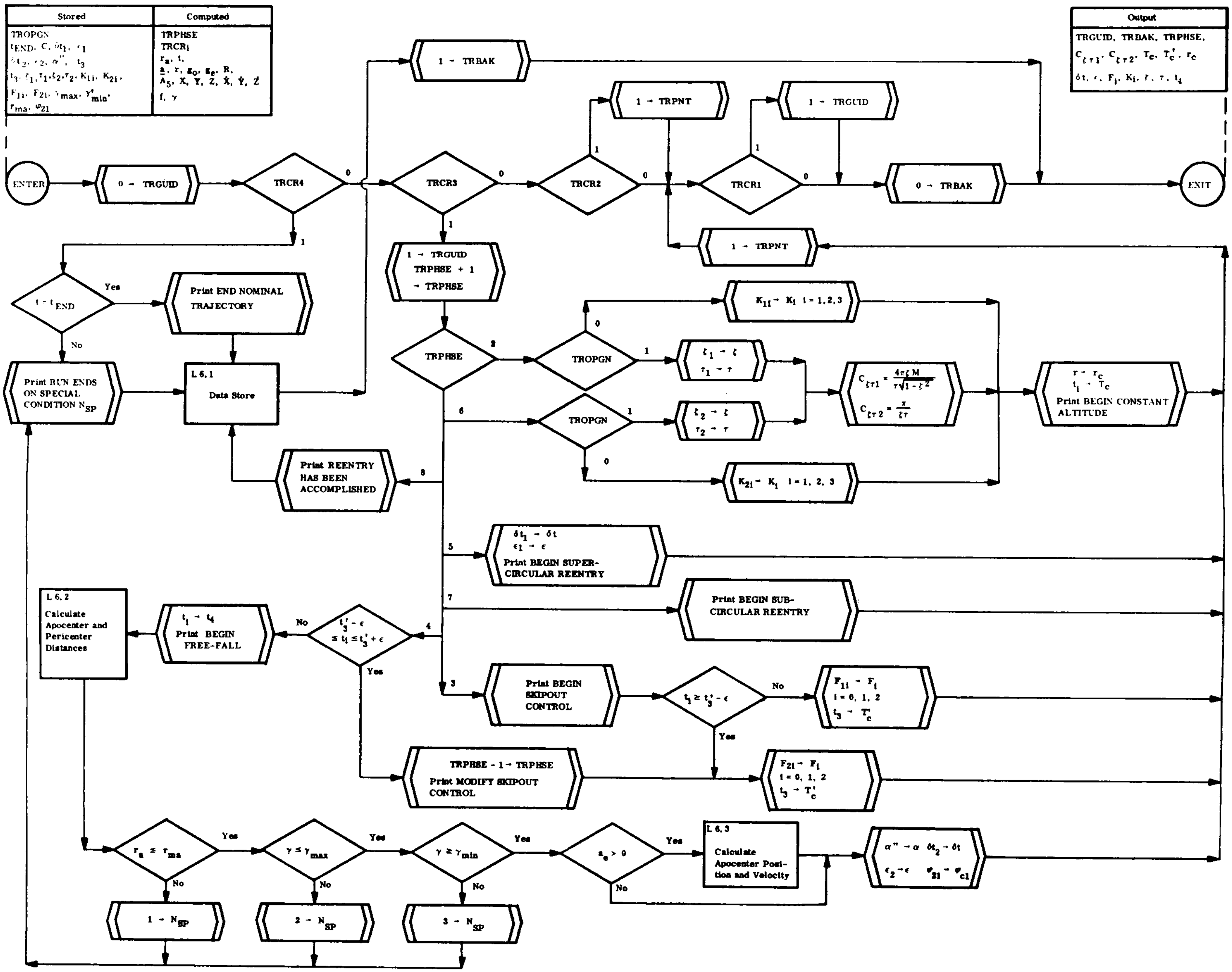
$$\alpha_3 = \tan^{-1}\left[\frac{\underline{Y}_A \cdot \underline{R}_{Oo}}{\underline{R}_O \cdot \underline{R}_{Oo}}\right] \qquad -\pi < \alpha_3 \le \pi$$

$$\left.\begin{aligned} \dot{\alpha}_1 &= \frac{\alpha_{1i} - \alpha_{1(i-1)}}{t_i - t_{i-1}} \\ \dot{\alpha}_2 &= \frac{\alpha_{2i} - \alpha_{2(i-1)}}{t_i - t_{i-1}} \\ \dot{\alpha}_3 &= \frac{\alpha_{3i} - \alpha_{3(i-1)}}{t_i - t_{i-1}} \end{aligned}\right\} \qquad \dot{\alpha}_1 = \dot{\alpha}_2 = \dot{\alpha}_3 = 0 \quad \text{at } t = t_o$$

$$\omega_{RO} = \cos\alpha_2 \cos\alpha_3(\dot{\alpha}_1) - \sin\alpha_3(\dot{\alpha}_2)$$

$$\omega_{YA} = \cos\alpha_2 \sin\alpha_3(\dot{\alpha}_1) + \cos\alpha_3(\dot{\alpha}_2)$$

$$\omega_{PI} = -\sin\alpha_2(\dot{\alpha}_1) + \dot{\alpha}_3$$



3.4.1.2.5 Outcontrol - Block I.6

Block I. 6. 1, Part A Data Store

Calculations required for printout in Part B which have not been previously made are accomplished here.

INPUT: $X, Y, Z, \dot{X}, \dot{Y}, \dot{Z}, f, r, g_e, R, A_5$

OUTPUT: $\theta, \phi, \beta, a', h$

1. $\underline{r}_t = A_5 \underline{r}$

2. $\underline{V}_t = A_5 \underline{V}$

3. $\theta = \cos^{-1}\left[\frac{Z_t}{r}\right]$

   a. If $Y_t \geq 0$ then $0 \leq \theta \leq \pi$

   b. If $Y_t < 0$ then $\pi < \theta < 2\pi$

4. $\phi' = \tan^{-1}\left[\frac{X_t}{Y_t}\right]$ $\quad - \pi < \phi \leq \pi$

   a. If $\frac{\sqrt{X_t^2 + Y_t^2}}{r} < 0.015$ then $\phi_i = \phi_{i-1}$

   b. If $\frac{\sqrt{X_t^2 + Y_t^2}}{r} \geq 0.015$ then $\phi_i = \phi'_i$

5. $\beta = \tan^{-1}\left[\frac{\cos \phi \dot{X}_t - \sin \phi \dot{Y}_t}{\cos \theta \sin \phi \dot{X}_t + \cos \theta \cos \phi \dot{Y}_t - \sin \theta \dot{Z}_t}\right]$ $\quad - \pi < \beta < \pi$

6. $a' = \frac{f}{g_e}$

7. $h = (r - R)$

Block I. 6. 1, Part B Data Store

Printout should have the following form.

1.	t	φ_c	φ	q_s	Q	a'	
2.	X	Y	Z	$\dot{X}$	$\dot{Y}$	$\dot{Z}$	
3.	r	θ	ϕ	V	γ	β	Phase No.
4.	a_x	a_y	a_z	α_1	α_2	α_3	
5.	$\Delta\varphi_c$	$\ddot{r}$	Δr	ω_{PI}	ω_{YA}	ω_{RO}	
6.	h	$\dot{r}$	$\lvert\underline{D}\rvert$	$\lvert\underline{N}\rvert$	E_n	NEXTT3	

At $t = t_o$ r_p should be printed in lieu of $\ddot{r}$

At $t = t_4$ r_p and r_a should be printed in lieu of $\ddot{r}$ and Δr, respectively.

At $t = t_4$ line 7 below should be printed.

7.	X_a	Y_a	Z_a	$\dot{X}_a$	$\dot{Y}_a$	$\dot{Z}_a$

Block I. 6. 2 Compute Apocenter and Pericenter Distances

INPUT: g_o, R, r, V, γ

OUTPUT: r_a, r_p

1. $\mu = g_o R^2$

2. $p = \dfrac{(r\ V \cos \gamma)^2}{\mu}$

3. $a_e = \dfrac{r\,\mu}{2\mu - r\ V^2}$

4. $e = +\sqrt{1 - p/a_e}$ Limit p/a_e to ≤ 1

5. Is $a_e < 0$?

   a. Yes: $r_a = 10^{20}$

   b. No: $r_a = a_e\ (1 + e)$

6. $r_p = a_e\ (1 - e)$

Block I. 6. 3 Compute Apocenter Position and Velocity

INPUT: r, $\dot{r}$, $\underline{r}$, $\underline{V}$, V, μ, $\underline{U}_p$, a_e

OUTPUT: $\underline{r}_a$, $\underline{V}_a$

1. $$\underline{P} = \frac{1}{\mu e}\left[\left(V^2 - \frac{\mu}{r}\right)\underline{r} - (r\,\dot{r})\,\underline{V}\right]$$

2. $$\underline{r}_a = - r_a \underline{P}$$

3. $$V_a = + \sqrt{\mu\left(\frac{2}{r_a} - \frac{1}{a_e}\right)}$$

4. $$\underline{V}_a = V_a \underline{P} \times \underline{U}_p$$

3.4.1.2.6 Data Store - Block I.7, Part A

Calculations required for printout in Part B which have not been previously made are accomplished here (this block is the same as Block I.6.1).

INPUT: $X, Y, Z, \dot{X}, \dot{Y}, \dot{Z}, f, r, g_e, R, A_5$

OUTPUT: $\theta, \varphi, \beta, a', h$

1. $\underline{r}_t = A_5 \underline{r}$

2. $\underline{V}_t = A_5 \underline{V}$

3. $\theta = \cos^{-1}\left[\frac{Z_t}{r}\right]$

   a. If $Y_t \geq 0$ then $0 \leq \theta \leq \pi$

   b. If $Y_t < 0$ then $\pi < \theta < 2\pi$

4. $\phi' = \tan^{-1}\left[\frac{X_t}{Y_t}\right]$

   a. If $\frac{\sqrt{X_t^2 + Y_t^2}}{r} < 0.015$ then $\phi_i = \phi_{i-1}$

   b. If $\frac{\sqrt{X_t^2 + Y_t^2}}{r} \geq 0.015$ then $\phi_i = \phi'_i$

5. $\beta = \tan^{-1}\left[\frac{\cos\phi \dot{X}_t - \sin\phi \dot{Y}_t}{\cos\theta \sin\phi \dot{X}_t + \cos\theta \cos\phi \dot{Y}_t - \sin\theta \dot{Z}_t}\right] \quad -\pi < \beta < \pi$

6. $a' = \frac{f}{g_e}$

7. $h = (r - R)$

Block I.7, Part B - Data Store

Printout should have the following form.

1.	t	φ_c	φ	q_s	Q	a'	
2.	X	Y	Z	$\dot{X}$	$\dot{Y}$	$\dot{Z}$	
3.	r	θ	ϕ	V	γ	β	Phase No.
4.	a_x	a_y	a_z	α_1	α_2	α_3	
5.	$\Delta\varphi_c$	$\ddot{r}$	Δr	ω_{PI}	ω_{YA}	ω_{RO}	
6.	h	$\dot{r}$	$\lvert \underline{D} \rvert$	$\lvert \underline{N} \rvert$	E_n	NEXTT3	

At $t = t_o$ r_p should be printed in lieu of $\ddot{r}$

At $t = t_4$ r_p and r_a should be printed in lieu of $\ddot{r}$ and Δr, respectively

At $t = t_4$ line 7 below should be printed.

7.	X_a	Y_a	Z_a	$\dot{X}_a$	$\dot{Y}_a$	$\dot{Z}_a$

3.4.1.2.7 Compute Evaluation Equations - Block I.8

INPUT: C_H, R_N, ρ, ρ_o, g, g_e, C_{e1}, C_{e2}, q_1, q_2, k_H, p_H, V, r, E_i

OUTPUT: q_s, E_n, a'

1. $$q_c = \frac{C_H}{\sqrt{R_N}} \left(\frac{\rho}{\rho_o}\right)^n \left(\frac{V}{\sqrt{g\,r}}\right)^m$$

2. If $\frac{V}{\sqrt{g\,r}} < 1.73$: $q_1 \rightarrow q$; $C_{e1} \rightarrow C_e$

   If $\frac{V}{\sqrt{g\,r}} \geq 1.73$: $q_2 \rightarrow q$; $C_{e2} \rightarrow C_e$

3. $$q_r = k_H R_N \left(\frac{\rho}{\rho_o}\right)^{p_H} C_e V^q$$

4. $$q_s = q_c + q_r$$

5. $$a' = \frac{\sqrt{a_x^2 + a_y^2 + a_z^2}}{g_e}$$

6. $$\tau' = E_o + E_1(a') + E_2(a')^2 + E_3(a')^3 + E_4(a')^4$$

7. $$\dot{E}'_n = \frac{1}{\tau'}$$

8. Is $\dot{E}'_n \leq 0.0008$?

   a. Yes: $\dot{E}_n = 0$

   b. No: $\dot{E}_n = \dot{E}'_n$

4.0 USER'S GUIDE

4.1 INTRODUCTION

This guide was written as an aid to the user in running the 133 program. The assumption is made that the user has read the symbol definitions, Section 3.1.3, and thus has a basic understanding of the input parameters. A description of the more troublesome inputs is presented with examples and hopefully helpful precautions. The program is unit independent in that only the input values must have consistent units. Angular values must be in radians.

4.1.1 Typical Flight

The program is used to simulate the flight of a lifting-type vehicle (e.g., an Apollo type vehicle) as it enters the atmosphere of a planet. The only control available is the roll angle (φ) of the vehicle. The flight path angle (α) is assumed to be constant. The trajectory generated is divided into seven phases, one of which is a skipout trajectory. This phase is optional since the simulation may be started in any phase. Once started in a particular phase, the program will proceed sequentially to termination. A sketch of a typical skipout-type trajectory is shown in Figure 5.

4.1.2 Program Termination Conditions

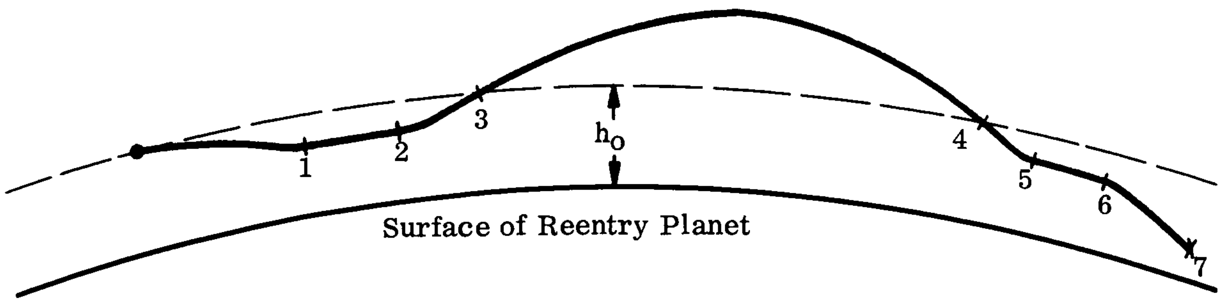
There are nine ways the program will terminate. The two standard conditions are (1) the end of phase 7 or (2) end on time (an input quantity). Seven special conditions are (1) apocenter distance greater than r_{ma} (calculated at start of phase 4), (2) flight path angle greater than γ_{max} at the start of phase 4, (3) flight path angle less than γ_{min} at start of phase 4, (4) radial distance greater than r_m and radial velocity positive in phase 1, 2, 4, and 6, (5) magnitude of aerodynamic acceleration greater than G_{max} in phase 1, 2, 5, and 6, (6) vehicle speed less than V_{IN} and radial acceleration negative in phase 3, and (7) program attempting to integrate backwards (probably caused by an input error). When special condition 7 occurs, some extra output data is included. This is described in the output section of the User's Guide.

4.2 DESCRIPTION OF INPUT DATA

The input data are arranged in groups (program flags, trajectory data, vehicle data, physical environment, program control, and trajectory constraints). The symbol definitions, Section 3.1.3, in most cases give a complete description of a particular input parameter. However, in some cases, further description will be helpful.

Program Flag Data

The first group of input consists of program flags. These are used to specify the type of input coordinates, starting phase number, and specify various program options.



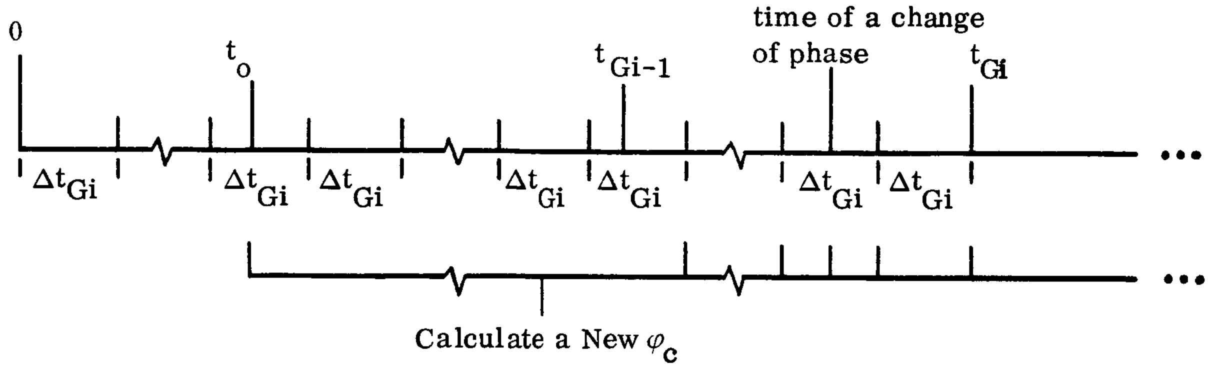
h_o - Height of atmosphere (at heights greater than this, the atmosphere is assumed to have little effect on the vehicle)

1. End of first supercircular velocity phase (constant roll angle control).
2. End of first constant altitude control phase.
3. End of skipout control phase (commanded roll angle is specified by input).
4. End of free-fall phase (in normal use, the roll angle has no effect in this phase). Constant roll angle control is used.
5. End of second supercircular velocity phase (constant roll angle control).
6. End of second constant altitude control phase.
7. End of subcircular velocity phase (constant roll angle control)

Figure 5. Trajectory Profile (Schematic)

Trajectory Data

The second group of input is the trajectory data. The initial position may be input in either cartesian or spherical coordinates. The frequency of calculation of a new control (new commanded roll angle φ_c) may be specified by the t_{Gi} and Δt_{Gi}. A new control is calculated every Δt_{Gi} time units (seconds are usually used) over the time interval $t_{Gi} - t_{Gi-1}$ according to the following scheme:



where t_{Gi} is an integer multiple of Δt_{Gi}.

Example: t_o = 1 sec, Δt_{G1} = 2 sec, t_{G2} = 12 sec

Δt_{G2} = 5 sec, t_{G2} = 20 sec

Assuming no phase change occurred during the first 19 seconds of the trajectory, a new φ_c would be calculated at the following times: 1, 2, 4, 6, 8, 10, 15, 20.

The initial body Euler angles may be set to zero unless the program is being started such that it matches some specific orientation of the re-entry vehicle.

The commanded roll angles φ_{c3}, φ_{11}, and φ_{21} are used in the constant attitude phases 7, 1, and 5, respectively (φ_{21} used also in the free-fall phase, 4). Here the commanded roll angle is set to plus or minus the input value, depending on which sign is required to correct for an out-of-plane velocity component. At the point where the magnitude of the sine of the angle between out-of-plane velocity and in-plane velocity exceeds ϵ_s, the sign of the commanded roll angle changes.

The commanded roll angle in the constant altitude phase (2 and 6) is calculated by

$$\varphi_c = \pm \left[\frac{\pi}{2} + \sin^{-1} (K_1 \Delta\dot{r} + K_2 \Delta r) + \frac{\pi}{2} e^{-K_3(t - T_c)} \right]$$

where

$$\Delta\dot{r} = \dot{r} ; \Delta r = r - r_c ; -\frac{\pi}{2} \le \sin^{-1} (\ ) \le \frac{\pi}{2}, \ |\varphi_c| \le \pi, \ e^{-K_3(t - T_c)} = 0 \text{ if } K_3 > 10$$

and the $\pm$ signs correct for out-of-plane velocity. The gains K_1 and K_2 will be input as constant if TROPGN = 0.

If TROPGN = 1, K_1 and K_2 will be calculated as a function of time with a damping ratio of ζ (ζ_1 in phase 2, ζ_2 in phase 6) and a natural frequency of τ (τ_1 in phase 2, τ_2 in phase 6). The intent of this control is to make $\Delta\dot{r}$ and Δr equal zero. Thus, the vehicle will be at a constant radial distance (r_c) with no radial velocity. The input constant K_3 ($K_3 = K_{13}$ in phase 2, $K_3 = K_{23}$ in phase 6) may be used to add 90° to the commanded roll angle at the beginning of phases 2 or 6. If, at the start of phases 2 or 6, $\Delta\dot{r}$ and Δr are both zero and radial acceleration is positive, φ_c should be equal to π (lift force directed downward) for a short time to keep the vehicle from "bouncing" off the atmosphere.

The angle of attack, α, is constant throughout the flight ($\alpha = \alpha'$ during phase 1, 2, 3; $\alpha = \alpha''$ during phases 4, 5, 6, 7).

The skipout control phase (phase 3) consists of two quadratic control laws

$$\varphi_c = \pm \{F_o + F_1 (t - T'_c) + F_2 (t - T'_c)^2\}$$

where

$$-\pi \le \varphi_c \le \pi$$

The F_0, F_1, F_2 are equal to F_{10}, F_{11}, F_{12}, respectively during $t_3 \le t < t'_3$. During the interval $t'_3 \le t < t_4$ (phase 3 modified) the F_0, F_1, F_2 are equal to F_{20}, F_{21}, F_{22}. If the program is started in the first part of phase 3, T'_c should equal t_3. If the program is started in the second (modified) part of phase 3, T'_c should equal t'_3.

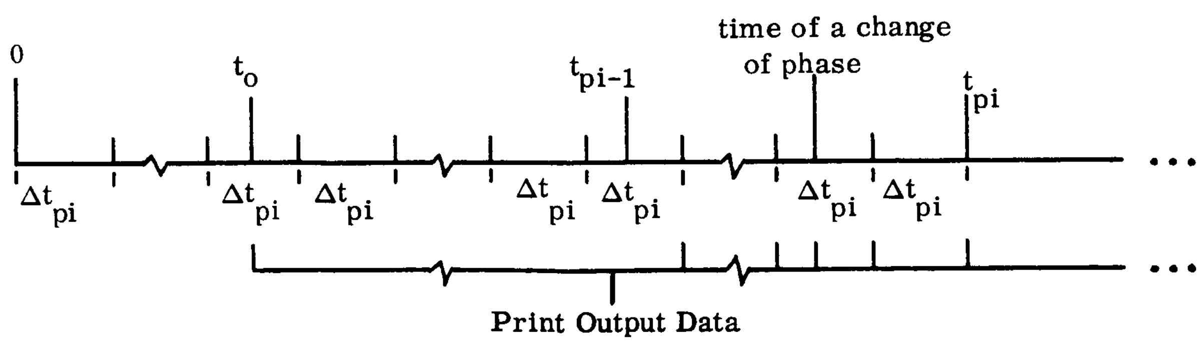
Values for the drag and normal force coefficients are given by the example problem at the end of the User's Guide.

Physical Environment Data

Values for the E_i, C_H, C_{E1}, C_{E2}, q_1, q_2, p_H, k_H, m and n may be found in the example at the end of the User's Guide.

Program Control Data

The printout specification scheme is similar to the nominal control calculation.



For example:

$$t_o = 1 \text{ sec}, \ \Delta t_{p1} = 5 \text{ sec}, \ t_{p1} = 35 \text{ sec}, \ \Delta t_{p2} = 2 \text{ sec}, \ t_{p2} = 50 \text{ sec}$$

Assume a phase change occurs at t = 44.6 seconds. Printout will occur at 1, 5, 10, 15, 20, 25, 30, 35, 40, 42, 44, 44.6, 46, 48, 50.

The δt_1 and δt_2 are the step sizes used by the integration routine. The ϵ_1 and ϵ_2 are the errors which are allowed between the present time and the time to which the routine is integrating. Thus, the integration routine will be left when time is to within an ϵ of the exit time.

The run number is printed at the top of each page of printout and is a convenient means of identification when many trajectories have been run at once (stacking runs).

Trajectory Constraint Data

All of these parameters have been explained in the beginning paragraphs of this guide where the nine ways in which the program will terminate are discussed.

4.3 INPUT PROCEDURE

The input data sheets (load sheets) are sectioned off according to column numbers on a standard IBM data processing card. The numbers in columns 1-5 correspond to the location (address) of the beginning of a data record. The letters in columns 7-9 specify the type of data being transmitted (BCI indicates an alphameric identification header, DEC indicates decimal numbers only). The numbers (or letters) in columns 11-72 are the input data. Columns 6 and 10 are left blank.

For DEC type data the first number appearing after column 10 will be placed in the location specified by columns 1-5. If a second number appears on the same card, it must be separated from the first by a comma, and it will be stored in the next successive location to the one punched in columns 1-5. The only limit to the number of numbers on a card is the 72nd column. The last number must not be followed by a comma. The DEC field is in free form where leading and trailing blanks are ignored. The DEC field may be ended on any particular card by an asterisk (*). Any characters appearing after an * will be ignored thus providing a convenient means of identification. The first BCI card is used for accounting identification. The second BCI can be filled with any identifying label 60 characters long.

Stacking runs is accomplished by establishing one deck of cards that provides a number for all the required locations. This deck is physically terminated with an "END" card where the letters END occur in columns 7, 8, and 9, respectively. After this card should be placed any cards (BCI and DEC) that provide the desired <u>changes</u> in data appearing in the first deck. When the first deck has been read in, computation will begin and continue until one of the nine termination conditions is reached. Next, the second group of cards will be read in replacing only those locations specified by the new cards. When the next END card is reached, computation will again begin. On the last run, the END card should be followed by a FIN card.

4.4 PROGRAM OPERATION PRECAUTIONS

Be sure that the maximum values of t_{Gi} and t_{pi} are greater than or equal to t_{END}.

If the program is started in phases 2 or 6 (TRPHSE = 2 or 6), be sure that T_c and r_c are set to the desired values of time and radial distance at the beginning of phase 2 or 6. Failure to do so will result in special condition number seven.

If the program is started in phase 3, T_c should be set equal to t_3 if $t_3 \leq t_o < t'_3$. T_c should be set equal to t'_3 if $t'_3 \leq t_o < t_4$. Failure to do so will result in special condition number seven.

The parameter r_s must be set to the desired radial distance for the start and end of phase 4.

The values of ϵ_1 and ϵ_2 should not be so small that they will become effectively zero as time reaches a large value. If the computer being used has seven significant digits and time has reached a value of 12,000.00 seconds only two significant digits remain to the right of the decimal. Thus, an ϵ of 0.005 is effectively zero. This condition will cause the integration routine to loop indefinetly. Thus, the smallest ϵ that can be used is 10^{-n} where n represents the number of digits to the right of the decimal point in the value of time at the end of the program.

4.5 INPUT SHEETS

The input data sheets for this program are presented on the following pages.

PROGRAM 133

Date ______
Page 1 of 5

Single Pass/Skipout Nominal Re-entry Trajectory

1 2 3 4 5	7 8 9	11 Engineer	Phone	Work Order Number	Date 72
1 1	BCI	133,	,	,	

HEADER

1 2 3 4 5	7 8 9	11 – 72
1 1	BCI	, TYPICAL EARTH SINGLE SKIPOUT SIMULATION - V*0 = 49, 980 FPS

PROGRAM FLAGS

1 2 3 4 5	7 8 9	TRINP (coord. flag)	TRPHSE (phase number)	TRSBCL (begin phase 7)
1 11	DEC	0. ,	1. ,	1.

1 2 3 4 5	7 8 9	TROPGN (variable gains)	TRACC (test $\dot{r}$, $\ddot{r}$ flag)
1 14	DEC	0. ,	0.

TRAJECTORY DATA

1 2 3 4 5	7 8 9	X_o (r_o)	Y_o (λ_o)	Z_o (μ_o)	(initial position)
1 16	DEC	2. 132569E7 ,	0. ,	0.	

1 2 3 4 5	7 8 9	$\dot{X}_o$ (V_o)	$\dot{Y}_o$ (γ_o)	$\dot{Z}_o$ (A_o)	(initial velocity)
1 19	DEC	49980. ,	-. 1228 ,	1. 5707963	

t_{Gi} i = 1, . . . , 10 (control interval definition time)

1 2 3 4 5	7 8 9				
1 22	DEC	500. ,	1920. ,	1. E6 ,	
1 26	DEC	,	,	,	
1 30	DEC	,			

Δt_{Gi} i = 1, . . . , 10 (nominal control calculation interval)

1 2 3 4 5	7 8 9				
1 32	DEC	1. ,	64. ,	1. ,	
1 36	DEC	,	,	,	
1 40	DEC	,			

Date ______
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PROGRAM 133

Single Pass/Skipout Nominal Re-entry Trajectory

TRAJECTORY DATA (con't)

		α_{10}	α_{20}	α_{30}	(initial body Euler angles)
1 42	DEC	0. ,	0. ,	0.	
		K_{φ} (roll rate gain)	β_{φ} (roll rate limit)	ϵ_s (bound on out-of-plane velocity)	
1 45	DEC	3. ,	.698 ,	.7	
		T_c (begin circular orbit)	r_c (circ. orbit rad. dist.)	φ_o (initial roll angle)	
1 48	DEC	0. ,	0. ,	.3926991	
		φ_{c3} (roll angle - ph. 7)	V_{IN} (velocity limit - ph. 7)		
1 51	DEC	0. ,	17000.		
		K_{11} (ζ_1) (gain - ph. 2)	K_{12} (τ_1) (gain - ph. 2)	K_{13} (trans. decay - ph. 2)	
1 53	DEC	.0137 ,	6.08 E-3 ,	.1	
		α' (attack angle - ph. 1,2,3)	φ_{11} (roll angle - ph. 1)		
1 56	DEC	.5411 ,	.3926991		
		K_{21} (ζ_2) (gain - ph. 6)	K_{22} (τ_2) (gain - ph. 6)	K_{23} (trans. decay - ph. 6)	
1 58	DEC	.0137 ,	6.08 E-3 ,	.1	
		α'' (attack angle - ph. 4,5,6,7)	φ_{21} (roll angle - ph. 4, 5)	T'_c (begin ph. 3 time)	
1 61	DEC	.5411 ,	.3926991 ,	0.	
		F_{10}	F_{11}	F_{12}	(ph. 3 control coeffs.)
1 64	DEC	0. ,	0. ,	0.	

PROGRAM 133

Single Pass/Skipout Nominal Re-entry Trajectory

Date ______
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TRAJECTORY DATA (con't)

F_{20} F_{21} F_{22} (modified ph. 3 control coeffs.)

1 67	DEC	0. ,	0. ,	0.

r_s (begin and end ph. 4) t_3 (begin ph. 3 time) t_3' (begin modified ph. 3 time)

1 70	DEC	2.132569E7 ,	250. ,	250.

C_{VPC} (test ph. 1,5 velocity) C_{APC} (test ph. 1,5 acceleration)

1 73	DEC	0. ,	0.

VEHICLE DATA

C_{DO} C_2 C_4 (drag coeffs.)

1 75	DEC	1.5057098 ,	-1,8170089 ,	.92657443

$C_{N\alpha}$ C_3 C_5 (normal force coeffs.)

1 78	DEC	1.3608741 ,	-1.3843004 ,	.29525989

M (mass of vehicle) R_N (heat sag. pt. radius) S (aero. area)

1 81	DEC	341.6149 ,	.75 ,	129.4

PHYSICAL ENVIRONMENT

E_i $i = 0, \ldots, 4$ (pilot g tolerance coeffs.)

1 84	DEC	22485.927 ,	-9927.7736 ,	1679.8636 ,	-127.17953
1 88	DEC	3.605921			

C_H (convective heating rate constant)

1 89	DEC	19800.

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Single Pass/Skipout Nominal Re-entry Trajectory

Date ________
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PHYSICAL ENVIRONMENT (con't)

C_{E1} C_{E2} (radiative heating rate constants)

1 90	DEC	0. ,	3.3343024E-10	

q_1 q_2 p_H (radiative heating rate exponents)

1 92	DEC	0. ,	5.05 ,	1.8

K_H (radiative heating rate constant)

1 95	DEC	.00175

m n (convective heating rate exponents)

1 96	DEC	3. ,	.5

g_o (planet's grav. accel.) g_e (earth's grav. accel.)

1 98	DEC	32.2 ,	32.2

ρ_o (planets atmos. density) β' (planet's atmos. decay factor)

1 100	DEC	.0027 ,	4.2553191E-5

R (radius of planet)

1 102	DEC	2.0925739E7

PROGRAM CONTROL

t_{pi} i = 1,...,10 (print interval definition time)

1 104	DEC	35. ,	375. ,	2100. ,	2170.
1 108	DEC	,	,	,	
1 112	DEC	2300. ,	1.E6		

Δt_{pi} i = 1,...,10 (print interval)

1 114	DEC	35. ,	125. ,	350. ,	70.
1 118	DEC	2300. ,	250. ,	,	
1 122	DEC	,			

PROGRAM 133

Single Pass/Skipout Nominal Re-entry Trajectory

Date ________
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PROGRAM CONTROL (con't)

		t_o (initial time)	t_{END} (end time)	V_{END} (velocity on which program ends)
1 124	DEC	0. ,	2. E4 ,	1000.
		δt_1 ($\int$ step size - ph. 1,2,3,5,6,7)		ϵ_1 (max. $\int$ error - ph. 1,2,3,5,6,7)
1 127	DEC	.5 ,		.001
		δt_2 ($\int$ step size - ph. 4)		ϵ_2 (max. $\int$ error - ph. 4)
1 129	DEC	64. ,		.01
		RUN NUMBER		
1 141	DEC	1.		

TRAJECTORY CONSTRAINTS

		G_{max} (accel. bound)	r_m (max. rad. dist. - ph. 2,6)	r_{am} (max. apogee distance)
1 143	DEC	10. ,	2.1425 E7 ,	2.336E7
		γ_{max}	γ_{min} (limits on γ at beginning of ph. 4)	
1 146	DEC	4. ,	-4.	
**	END			
	FIN			

** An END card must terminate each run and a FIN card terminates a set of one or more runs.

Note: All numbers must have a decimal point.

4.6 OUTPUT DATA

The output will appear in the following matrix form. See the example at the end of the User's Guide for comparison with printed symbols.

1.	t	φ_c	φ	q_s	Q	a'	
2	X	Y	Z	$\dot{X}$	$\dot{Y}$	$\dot{Z}$	
3.	r	θ	φ	V	γ	β	Phase
4.	a_x	a_y	a_z	α_1	α_2	α_3	No.
5.	$\Delta\varphi_c$	$\ddot{r}$	Δr	ω_{PI}	ω_{YA}	ω_{RO}	
6.	h	$\dot{r}$	$\lvert\underline{D}\rvert$	$\lvert\underline{N}\rvert$	E_n	NEXTT3	

Exceptions:

at $t = t_o$ — r printed in lieu of $\ddot{r}$

at $t = t_4$ — r_p and r_a printed in lieu of $\ddot{r}$ and Δr, respectively; also an extra line of print occurs at this time as follows:

5.	$\Delta\varphi_c$	r_p	r_a	ω_{PI}	ω_{YA}	ω_{RO}
7.	X_a	Y_a	Z_a	$\dot{X}_a$	$\dot{Y}_a$	$\dot{Z}_a$

If the run ends on special condition 7, extra printout occurs as follows:

TRCR1 NEXTT1 TRCR2 NEXTT2 TRCR3 NEXTT3 TRCR4 NEXTT4 I*G I*P

T*+ T*SAFE

R*M G*M V COS (GAMMA) V. V*IN TRSBCL

The values of these parameters may give information as to why the error condition occurred. The TRCRi and NEXTTi are in the symbols definition (3.1.3 - TRCRi are flags).

I*G = i in t_{Gi} and Δt_{Gi}

I*P = j in t_{pj} and Δt_{pj}

T*+ = time to which the integration routine is required to integrate to within ϵ_1 or ϵ_2, depending on the phase.

T*SAFE = $t_i - 1000\,\epsilon_1$ (or $1000\,\epsilon_2$) If NEXTT3 is the minimum of all four NEXTTi and NEXTT3 $> t_i - 1000\,\epsilon_{1,2}$ then NEXTT3 is set equal to t_i. Thus, if NEXTT3 is calculated to be a negative number (the program exceeded the time to change phase), the program will not try to integrate backwards unless NEXTT3 $< t_i - 1000\,\epsilon_{1,2}$ at which point the program will terminate on special condition number 7.

R*M = r_m

G*M = G_{max}

V COS (GAMMA) = $V \cos \gamma$

V. = $\dot{V}$

V*IN = V_{IN}

4.7 REPRESENTATIVE EXAMPLE

The program was used to simulate a single skipout type re-entry trajectory at earth. The vehicle used as an Apollo type with a lift-to-drag ratio of 0.5. The initial height, velocity, and flight path angle were about 400,000 ft, 50,000 ft/sec, and -0.1228 radians, respectively. A printout of the IBM cards punched from the load sheets preceeds the run, shown in Figure 6. The program was started in phase 1 and ran through all 7 phases. The final printout, phase 8, occurs only once when the vehicle has reached a speed equal to V_{END} in phase 7. This particular run took about 15 minutes of IBM 7040 computer time (on-line printer). A brief discussion of the input follows the input deck listing and simulation printout.

4.7.1 Input Deck Listing

```
1   1 BCI , TYPICAL EARTH SINGLE SKIPOUT SIMULATION - V*0 = 49,980 FPS
1  11 DEC 0., 1., 1.                               * TRINP, TRPHSE, TRSBCL
1  14 DEC 0., 0.                                   * TROPGN, TRACC
1  16 DEC 2.132569 E7, 0., 0.                      * R*0, LAM*0, MU*0
1  19 DEC 49980., -.1228, 1.5707963                * V*0, GAM*0, A*0
1  22 DEC 500., 1920., 1. E6                       * T*G1, T*G2, T*G3
1  32 DEC 1., 64., 1.                              * DELT*G1, DELT*G2, DELT*G3
1  42 DEC 0., 0., 0.                               * ALPH*10, ALPH*20, ALPH*30
1  45 DEC 3., .698, .7                             * K*PHI, BTA*PHI, EPS*S
1  48 DEC 0., 0., .3926991                         * T*C, R*C, PHI*0
1  51 DEC 0., 17000.                               * PHI*C3, V*IN
1  53 DEC .0137, 6.08 E-3, .1                      * K*11, K*12, K*13
1  56 DEC .5411, .3926991                          * ALPHP, PHI*11
1  58 DEC .0137, 6.08 E-3, .1                      * K*21, K*22, K*23
1  61 DEC .5411, .3926991, 0.                      * ALPHPP, PHI*21, T*CP
1  64 DEC 0., 0., 0.                               * F*10, F*11, F*12
1  67 DEC 0., 0., 0.                               * F*20, F*21, F*22
1  70 DEC 2.132569 E7, 250., 250.                  * R*S, T*3, T*3P
1  73 DEC 0.,0.                                    * C*VPC, C*APC
1  75 DEC 1.5057098, -1.8170089, .92657443         * C*DO, C*2, C*4
1  78 DEC 1.3608741, -1.3843004, .29525989         * C*NALPH, C*3, C*5
1  81 DEC 341.6149, .75, 129.4                     * M, R*N, S
1  84 DEC 22485.927, -9927.7736, 1679.8636         * E*0, E*1, E*2
1  87 DEC -127.17953, 3.605921                     * E*3, E*4
1  89 DEC 19800.                                   * C*H
1  90 DEC 0., 3.3343024 E-10                       * C*E1, C*E2
1  92 DEC 0., 5.05, 1.8                            * Q*1, Q*2, P*H
1  95 DEC .00175                                   * K*H
1  96 DEC 3., .5                                   * M-EX, N-EX
1  98 DEC 32.2, 32.2                               * G*0, G*E
1 100 DEC .0027, 4.2553191 E-5                     * RHO*0, BETAP
1 102 DEC 2.0925739 E7                             * CAPR
1 104 DEC 35., 375., 2100., 2170.                  * T*P1, T*P2, T*P3, T*P4
1 108 DEC 2300., 1. E6                             * T*P5, T*P6
1 114 DEC 35., 125., 350., 70.                     * DELT*PI,  I=1,2,3,4
1 118 DEC 2300., 250.                              * DELT*P5, DELT*P6
1 124 DEC 0., 2. E4, 1000.                         * T*0, T*END, V*END
1 127 DEC .5, .001                                 * DELT*1, EPI*1
1 129 DEC 64., .01                                 * DELT*2, EPI*2
1 141 DEC 1.                                       * RUN NUMBER
1 143 DEC 10., 2.1425 E7, 2.336 E7                 * G*MAX, R*M, R*MA
1 146 DEC 4., -4.                                  * GA*MAX, GA*MIN
      END
```

Figure 6

```
                                                                                                   PAGE    1
INPUTS TO PROGRAM 133         RUN     1.0          LABEL   TYPICAL EARTH SINGLE SKIPOUT SIMULATION - V*O = 49,980 FPS

   PROGRAM FLAGS

      TRINP    TRPHSE    TRSBCL    TROPGN    TRACC
       0.0       1.0       1.0       0.0      0.0

   TRAJECTORY DATA

      R*O                 LAM*O               MU*O                V*O                 GAM*O               A*O
       0.21325690E 08      0.                  0.                  0.49980000E 05     -0.12280000E 00      0.15707963E 01

      T*G   NOMINAL CONTROL INTERVAL
       0.50000000E 03      0.19200000E 04      0.10000000E 07      0.                  0.
       0.                  0.                  0.                  0.                  0.

      DELT*G
       0.10000000E 01      0.63999999E 02      0.10000000E 01      0.                  0.
       0.                  0.                  0.                  0.                  0.

      ALPH*10             ALPH*20             ALPH*30             K*PHI               BTA*PHI             EPS*S
       0.                  0.                  0.                  0.30000000E 01      0.69799999E 00      0.69999999E 00

      T*C                 R*C                 PHI*O               PHI*C3              V*IN
       0.                  0.                  0.39269910E 00      0.                  0.17000000E 05

      K*11                K*12                K*13                ALPHP               PHI*11
       0.13700000E-01      0.60800000E-02      0.99999999E-01      0.54110000E 00      0.39269910E 00

      K*21                K*22                K*23                ALPHPP              PHI*21              T*CP
       0.13700000E-01      0.60800000E-02      0.99999999E-01      0.54110000E 00      0.39269910E 00      0.

      F*10                F*11                F*12                F*20                F*21                F*22
       0.                  0.                  0.                  0.                  0.                  0.

      R*S                 T*3                 T*3P                C*VPC               C*APC
       0.21325690E 08      0.25000000E 03      0.25000000E 03      0.                  0.

   VEHICLE DATA

      C*D*O               C*2                 C*4                 C*NALP              C*3                 C*5
       0.15057098E 01     -0.18170089E 01      0.92657442E 00      0.13608741E 01     -0.13843004E 01      0.29525989E 00

      M                   R*N                 S
       0.34161490E 03      0.75000000E 00      0.12940000E 03
```

4.7.2 Simulation Printout

```
                                                                                              PAGE    2

INPUTS TO PROGRAM 133(CONTINUED)          RUN     1.0

   PHYSICAL ENVIRONMENT

      E*0               E*1                E*2               E*3                E*4               C*H
       0.22485927E 05   -0.99277735E 04     0.16798636E 04   -0.12717953E 03     0.36059210E 01    0.19800000E 05

      C*E1              C*E2               Q*1               Q*2                PH                KH
       0.                0.33343024E-09     0.                0.50500000E 01     0.18000000E 01    0.17500000E-02

      M-EX              N-EX               G*0               G*E                RHO*0             BETAP
       0.30000000E 01    0.50000000E 00     0.32200000E 02    0.32200000E 02     0.27000000E-02    0.42553191E-04

      CAPR
       0.20925739E 08

   PROGRAM CONTROL

      T*P  PRINT INTERVAL
       0.35000000E 02    0.37500000E 03     0.21000000E 04    0.21700000E 04     0.23000000E 04
       0.10000000E 07    0.                 0.                0.                 0.

      DELT*P
       0.35000000E 02    0.12500000E 03     0.35000000E 03    0.69999999E 02     0.23000000E 04
       0.25000000E 03    0.                 0.                0.                 0.

      T*0               T*END              V*END             DELT1              EPI1
       0.                0.20000000E 05     0.10000000E 04    0.50000000E 00     0.99999998E-03

      DELT2             EPI2
       0.63999999E 02    0.99999998E-02

   TRAJECTORY CONSTRAINTS

      G*MAX             R*M                R*MA              GAMAX              GAMIN
       0.10000000E 02    0.21425000E 08     0.23360000E 08    0.40000000E 01    -0.40000000E 01
```

Simulation Printout (cont'd.)

```
RUN NO.  1          TYPICAL EARTH SINGLE SKIPOUT SIMULATION - V*0 = 49,980 FPS                 PHASE NO. 1          PAGE NO.   3

 START OF PROGRAM --- T = T*0
       TIME                 PHI*C                PHI                  Q*S                  Q                    A PRIME
 1     0.                   0.39269910E 00       0.39269910E 00       0.33847811E 02       0.                   0.19000274E-02     PHASE
       X                    Y                    Z                    X DOT                Y DOT                Z DOT
 2     0.21325690E 08       0.                   0.                   -0.61221299E 04      0.49603628E 05       0.15273876E-02       1
       R                    THETA                PHI SMALL            V                    GAMMA                BETA
 3     0.21325690E 08       0.15707963E 01       0.                   0.49979999E 05       -0.12280000E 00      0.
       A*X                  A*Y                  A*Z                  ALPHA*1              ALPHA*2              ALPHA*3
 4     0.31939177E-01       -0.51107360E-01      -0.10536949E-01      0.                   0.                   0.
       DELTA PHI*C          R*P                  DELTA R              OMEGA*PI             OMEGA*YA             OMEGA*RO
 5     0.                   0.21107398E 08       0.                   0.                   0.                   0.
       H                    R DOT                MAG D BAR            MAG N BAR            E*N                  NEXTT3
 6     0.39995100E 06       -0.61221299E 04      0.18664055E 02       0.94061504E 01       0.                   0.10000000E 03

       TIME                 PHI*C                PHI                  Q*S                  Q                    A PRIME
 1     0.35000000E 02       0.39269910E 00       0.39269910E 00       0.35971788E 04       0.22314434E 05       0.17811918E 01     PHASE
       X                    Y                    Z                    X DOT                Y DOT                Z DOT
 2     0.21093517E 08       0.17337476E 07       -0.38562665E 03      -0.70103568E 04      0.49242630E 05       -0.65631486E 02      1
       R                    THETA                PHI SMALL            V                    GAMMA                BETA
 3     0.21164648E 08       0.16528054E 01       0.18284292E-04       0.49739180E 05       -0.59404208E-01      0.13244569E-02
       A*X                  A*Y                  A*Z                  ALPHA*1              ALPHA*2              ALPHA*3
 4     0.30828997E 02       -0.47358311E 02      -0.98126381E 01      -0.42847805E-02      -0.71589235E-02      0.16706526E-01
       DELTA PHI*C          R DOT DOT            DELTA R              OMEGA*PI             OMEGA*YA             OMEGA*RO
 5     0.                   0.10894054E 03       0.                   0.95708782E-04       -0.21289820E-03      -0.11474084E-03
       H                    R DOT                MAG D BAR            MAG N BAR            E*N                  NEXTT3
 6     0.23890950E 06       -0.29529791E 04      0.17496727E 05       0.88178509E 04       0.                   0.62119520E 02
```

Simulation Printout (cont'd.)

RUN NO. 1 TYPICAL EARTH SINGLE SKIPOUT SIMULATION - V*O = 49,980 FPS PHASE NO. 2 PAGE NO. 4

BEGIN CONSTANT ALTITUDE

	TIME	PHI*C	PHI	Q*S	Q	A PRIME	
1	0.55513826E 02	0.31382176E 01	0.39269910E 00	0.24794939E 05	0.34318137E 06	0.62839708E 01	PHASE
	X	Y	Z	X DOT	Y DOT	Z DOT	
2	0.20956320E 08	0.27228361E 07	-0.58823867E 04	-0.60698285E 04	0.46713342E 05	-0.55966951E 03	2
	R	THETA	PHI SMALL	V	GAMMA	BETA	
3	0.21132468E 08	0.17000016E 01	0.28070149E-03	0.47109365E 05	-0.52295519E-05	0.11916696E-01	
	A*X	A*Y	A*Z	ALPHA*1	ALPHA*2	ALPHA*3	
4	0.10675666E 03	-0.16874610E 03	-0.32723182E 02	-0.67202174E-02	-0.11631166E-01	0.14162868E-02	
	DELTA PHI*C	R DOT DOT	DELTA R	OMEGA*PI	OMEGA*YA	OMEGA*RO	
5	-0.33751503E-02	0.15856209E 03	0.	-0.13158128E-02	-0.21990808E-03	-0.13150100E-03	
	H	R DOT	MAG D BAR	MAG N BAR	E*N	NEXTT3	
6	0.20672950E 06	-0.24636087E 00	0.61727727E 05	0.31109012E 05	0.15155406E-01	0.55513826E 02	

	TIME	PHI*C	PHI	Q*S	Q	A PRIME	
1	0.12500000E 03	0.31415927E 01	0.31415927E 01	0.81100926E 03	0.69881874E 06	0.34288267E 01	PHASE
	X	Y	Z	X DOT	Y DOT	Z DOT	
2	0.20384222E 08	0.55879109E 07	-0.63438413E 05	-0.99386245E 04	0.36450498E 05	-0.99895060E 03	2
	R	THETA	PHI SMALL	V	GAMMA	BETA	
3	0.21136350E 08	0.18383516E 01	0.31121315E-02	0.37794350E 05	0.14450856E-02	0.27252901E-01	
	A*X	A*Y	A*Z	ALPHA*1	ALPHA*2	ALPHA*3	
4	-0.22012712E 02	-0.10815653E 03	0.27532253E 01	0.27865808E 01	-0.17555835E 00	-0.11886892E 01	
	DELTA PHI*C	R DOT DOT	DELTA R	OMEGA*PI	OMEGA*YA	OMEGA*RO	
5	0.15707963E 01	-0.13886357E 02	0.38812500E 04	-0.21520853E-02	0.69453646E-09	0.17283131E-08	
	H	R DOT	MAG D BAR	MAG N BAR	E*N	NEXTT3	
6	0.21061075E 06	0.54616053E 02	0.33681518E 05	0.16974523E 05	0.37805460E-01	0.25000000E 03	

Simulation Printout (cont'd.)

```
RUN NO.  1          TYPICAL EARTH SINGLE SKIPOUT SIMULATION - V*O = 49,980 FPS                PHASE NO. 3        PAGE NO.   5

 BEGIN SKIPOUT CONTROL
        TIME            PHI*C             PHI              Q*S              Q                A PRIME
1       0.25000000E 03  -0.               0.31415927E 01   0.32451396E 03   0.76661660E 06   0.18389762E 01   PHASE
        X               Y                 Z                X DOT            Y DOT            Z DOT
2       0.18947812E 08   0.93650733E 07  -0.19879576E 06  -0.12451900E 05   0.24981946E 05  -0.11314754E 04     3
        R               THETA             PHI SMALL        V                GAMMA            BETA
3       0.21136785E 08   0.20298165E 01   0.10491383E-01   0.27936135E 05  -0.29697590E-02   0.45191807E-01
        A*X             A*Y               A*Z              ALPHA*1          ALPHA*2          ALPHA*3
4      -0.28483540E 00  -0.59165871E 02   0.23955802E 01   0.27760909E 01  -0.16436905E 00  -0.13829239E 01
        DELTA PHI*C     R DOT DOT         DELTA R          OMEGA*PI         OMEGA*YA         OMEGA*RO
5       0.15707963E 01  -0.21048588E 02   0.43895000E 04  -0.20819604E-02  -0.69576957E-09  -0.36597394E-08
        H               R DOT             MAG D BAR        MAG N BAR        E*N              NEXTT3
6       0.21104625E 06  -0.82963468E 02   0.18064345E 05   0.91039142E 04   0.37805460E-01   0.25000000E 03

        TIME            PHI*C             PHI              Q*S              Q                A PRIME
1       0.37500000E 03   0.               0.               0.31620122E 02   0.78536196E 06   0.24896514E-01   PHASE
        X               Y                 Z                X DOT            Y DOT            Z DOT
2       0.17366313E 08   0.12213141E 08  -0.33815650E 06  -0.13807199E 05   0.21384829E 05  -0.10685261E 04     3
        R               THETA             PHI SMALL        V                GAMMA            BETA
3       0.21233557E 08   0.21836218E 01   0.19469541E-01   0.25477272E 05   0.40229321E-01   0.52549814E-01
        A*X             A*Y               A*Z              ALPHA*1          ALPHA*2          ALPHA*3
4       0.69116047E 00  -0.40540009E 00   0.24883431E-01  -0.36758725E 00   0.16253083E 00   0.41118360E 00
        DELTA PHI*C     R DOT DOT         DELTA R          OMEGA*PI         OMEGA*YA         OMEGA*RO
5       0.15707963E 01  -0.40376687E 00   0.43895000E 04   0.12120499E-02   0.36528171E-08  -0.56032449E-08
        H               R DOT             MAG D BAR        MAG N BAR        E*N              NEXTT3
6       0.30781850E 06   0.10246569E 04   0.24455957E 03   0.12325104E 03   0.37805460E-01   0.46487869E 03
```

Simulation Printout (cont'd.)

```
RUN NO.  1         TYPICAL EARTH SINGLE SKIPOUT SIMULATION - V*O = 49,980 FPS                 PHASE NO. 4        PAGE NO.  6

 BEGIN FREE FALL
        TIME               PHI*C              PHI                Q*S                Q                  A PRIME
1       0.46785504E 03     0.39269910E 00     0.                 0.44139979E 01     0.78662972E 06     0.48872723E-03    PHASE
        X                  Y                  Z                  X DOT              Y DOT              Z DOT
2       0.15978395E 08     0.14116895E 08    -0.43499105E 06    -0.16058986E 05     0.19585780E 05    -0.10154131E 04      4
        R                  THETA              PHI SMALL          V                  GAMMA              BETA
3       0.21325689E 08     0.22942358E 01     0.27217006E-01     0.25348074E 05     0.37627390E-01     0.57356890E-01
        A*X                A*Y                A*Z                ALPHA*1            ALPHA*2            ALPHA*3
4       0.14382476E-01    -0.63729096E-02     0.42906923E-03    -0.36758724E 00     0.16253083E 00     0.52456610E 00
        DELTA PHI*C        R*P                R*A                OMEGA*PI           OMEGA*YA           OMEGA*RO
5       0.15707963E 01     0.19765829E 08     0.21715646E 08     0.12219927E-02     0.18855182E-08    -0.10910377E-08
        H                  R DOT              MAG D BAR          MAG N BAR          E*N                NEXTT3
6       0.39995050E 06     0.95355684E 03     0.48007895E 01     0.24194608E 01     0.37805460E-01     0.46785504E 03
        X*A                Y*A                Z*A                X DOT*A            Y DOT*A            Z DOT*A
7      -0.93755289E 06     0.21674974E 08    -0.94233243E 06    -0.24850690E 05    -0.10845322E 04    -0.22112492E 03


        TIME               PHI*C              PHI                Q*S                Q                  A PRIME
1       0.69999999E 03     0.39269910E 00     0.39269910E 00     0.69798447E-01     0.78685515E 06     0.12347874E-06    PHASE
        X                  Y                  Z                  X DOT              Y DOT              Z DOT
2       0.11682357E 08     0.18061156E 08    -0.65093622E 06    -0.20693364E 05     0.14200756E 05    -0.83380806E 03      4
        R                  THETA              PHI SMALL          V                  GAMMA              BETA
3       0.21519910E 08     0.25667475E 01     0.55662087E-01     0.25111193E 05     0.28275082E-01     0.79113056E-01
        A*X                A*Y                A*Z                ALPHA*1            ALPHA*2            ALPHA*3
4       0.38696564E-05    -0.67574369E-06    -0.61467858E-06    -0.28087829E 00    -0.22060528E 00     0.80447552E 00
        DELTA PHI*C        R DOT DOT          DELTA R            OMEGA*PI           OMEGA*YA           OMEGA*RO
5       0.15707963E 01    -0.11117721E 01     0.43895000E 04     0.11192449E-02    -0.40607353E-03    -0.22410736E-03
        H                  R DOT              MAG D BAR          MAG N BAR          E*N                NEXTT3
6       0.59417125E 06     0.70992643E 03     0.12129372E-02     0.61128573E-03     0.37805460E-01     0.10000000L 07


        TIME               PHI*C              PHI                Q*S                Q                  A PRIME
1       0.10500000E 04     0.39269910E 00     0.39269910E 00     0.17884335E-02     0.78686035E 06     0.81827068E-10    PHASE
        X                  Y                  Z                  X DOT              Y DOT              Z DOT
2       0.36558951E 07     0.21363125E 08    -0.87946008E 06    -0.24501297E 05     0.44366769E 04    -0.45487873E 03      4
        R                  THETA              PHI SMALL          V                  GAMMA              BETA
3       0.21691522E 08     0.29673642E 01     0.23607405E 00     0.24903907E 05     0.10379899E-01     0.25048963E 00
        A*X                A*Y                A*Z                ALPHA*1            ALPHA*2            ALPHA*3
4       0.25156030E-08     0.63830964E-09    -0.45457671E-09    -0.44552524E 00    -0.22246308E 00     0.12318381E 01
        DELTA PHI*C        R DOT DOT          DELTA R            OMEGA*PI           OMEGA*YA           OMEGA*RO
5       0.15707963E 01    -0.13690825E 01     0.43895000E 04     0.11123135E-02    -0.39852222E-03    -0.23097322E-03
        H                  R DOT              MAG D BAR          MAG N BAR          E*N                NEXTT3
6       0.76578324E 06     0.25849539E 03     0.80379094E-06     0.40508769E-06     0.37805460E-01     0.10000000L 07
```

Simulation Printout (cont'd.)

RUN NO. 1 TYPICAL EARTH SINGLE SKIPOUT SIMULATION - V*O = 49,980 FPS PHASE NO. 4 PAGE NO. 7

	TIME	PHI*C	PHI	Q*S	Q	A PRIME	
1	0.14000000E 04	0.39269910E 00	0.39269910E 00	0.16096627E-02	0.78686077E 06	0.66303892E-10	PHASE
	X	Y	Z	X DOT	Y DOT	Z DOT	
2	-0.49847145E 07	0.21094199E 08	-0.96101307E 06	-0.24176442E 05	-0.59505150E 04	-0.46092296E 01	4
	R	THETA	PHI SMALL	V	GAMMA	BETA	
3	0.21696454E 08	0.33777607E 01	0.29511372E 01	0.24897971E 05	-0.92638820E-02	0.29338253E 01	
	A*X	A*Y	A*Z	ALPHA*1	ALPHA*2	ALPHA*3	
4	0.16433156E-08	0.13009954E-08	-0.40630928E-09	-0.59490117E 00	-0.15838603E 00	0.16498133E 01	
	DELTA PHI*C	R DOT DOT	DELTA R	OMEGA*PI	OMEGA*YA	OMEGA*RO	
5	0.15707963E 01	-0.13962743E 01	0.43895000E 04	0.11139422E-02	-0.40246384E-03	-0.22389646E-03	
	H	R DOT	MAG D BAR	MAG N BAR	E*N	NEXTT3	
6	0.77071549E 06	-0.23064857E 03	0.65130610E-06	0.32823968E-06	0.37805460E-01	0.38409133E 04	

	TIME	PHI*C	PHI	Q*S	Q	A PRIME	
1	0.17500000E 04	0.39269910E 00	0.39269910E 00	0.51679335E-01	0.78686477E 06	0.67742901E-07	PHASE
	X	Y	Z	X DOT	Y DOT	Z DOT	
2	-0.12789940E 08	0.17301794E 08	-0.88201312E 06	-0.19771506E 05	-0.15446649E 05	0.45130557E 03	4
	R	THETA	PHI SMALL	V	GAMMA	BETA	
3	0.21533986E 08	0.37792973E 01	0.30727401E 01	0.25094124E 05	-0.27348069E-01	0.28748996E 01	
	A*X	A*Y	A*Z	ALPHA*1	ALPHA*2	ALPHA*3	
4	0.98036727E-06	0.18966233E-05	-0.44706085E-06	-0.70479551E 00	-0.40756774E-01	0.20517151E 01	
	DELTA PHI*C	R DOT DOT	DELTA R	OMEGA*PI	OMEGA*YA	OMEGA*RO	
5	0.15707963E 01	-0.12040925E 01	0.43895000E 04	0.11197681E-02	-0.40014679E-03	-0.23369645E-03	
	H	R DOT	MAG D BAR	MAG N BAR	E*N	NEXTT3	
6	0.60824750E 06	-0.68619031E 03	0.66544155E-03	0.33536354E-03	0.37805460E-01	0.20660874E 04	

Simulation Printout (cont'd.)

```
RUN NO.  1        TYPICAL EARTH SINGLE SKIPOUT SIMULATION - V*O = 49,980 FPS              PHASE NO. 5        PAGE NO.   8

 BEGIN SUPER-CIRCULAR REENTRY
      TIME               PHI*C              PHI                Q*S                Q                  A PRIME
1     0.20022955E 04     0.39269910E 00     0.39269910E 00     0.44135593E 01     0.78709086E 06     0.48868793E-03    PHASE
      X                  Y                  Z                  X DOT              Y DOT              Z DOT
2    -0.17127241E 08     0.12685010E 08    -0.73018328E 06    -0.14323142E 05    -0.20899287E 05     0.74448034E 03      5
      R                  THETA              PHI SMALL          V                  GAMMA              BETA
3     0.21325690E 08     0.40753436E 01     0.30989856E 01     0.25347324E 05    -0.37628705E-01     0.16156312E 00
      A*X                A*Y                A*Z                ALPHA*1            ALPHA*2            ALPHA*3
4     0.25720787E-02     0.15161198E-01    -0.33371202E-02    -0.75112866E 00     0.66745156E-01     0.23349668E 01
      DELTA PHI*C        R DOT DOT          DELTA R            OMEGA*PI           OMEGA*YA           OMEGA*RO
5     0.15707963E 01    -0.91219401E 00     0.43895000E 04     0.11289783E-02    -0.40100211E-03    -0.24088312E-03
      H                  R DOT              MAG D BAR          MAG N BAR          E*N                NEXTT3
6     0.39995100E 06    -0.95356190E 03     0.48004035E 01     0.24192663E 01     0.37805460E-01     0.20022955E 04

      TIME               PHI*C              PHI                Q*S                Q                  A PRIME
1     0.21000000E 04     0.39269910E 00     0.39269910E 00     0.35051934E 02     0.78851866E 06     0.30765058E-01    PHASE
      X                  Y                  Z                  X DOT              Y DOT              Z DOT
2    -0.18404118E 08     0.10559965E 08    -0.65263421E 06    -0.11777687E 05    -0.22540999E 05     0.83864376E 03      5
      R                  THETA              PHI SMALL          V                  GAMMA              BETA
3     0.21228526E 08     0.41917413E 01     0.31061462E 01     0.25446294E 05    -0.40407252E-01     0.91294885E-01
      A*X                A*Y                A*Z                ALPHA*1            ALPHA*2            ALPHA*3
4     0.46208235E-01     0.96664061E 00    -0.21172659E 00    -0.76074920E 00     0.11151496E 00     0.24443175E 01
      DELTA PHI*C        R DOT DOT          DELTA R            OMEGA*PI           OMEGA*YA           OMEGA*RO
5     0.15707963E 01    -0.40693974E 00     0.43895000E 04     0.11178458E-02    -0.40323567E-03    -0.24171104E-03
      H                  R DOT              MAG D BAR          MAG N BAR          E*N                NEXTT3
6     0.30278750E 06    -0.10279350E 04     0.30220654E 03     0.15230346E 03     0.37805460E-01     0.46240354E 04

      TIME               PHI*C              PHI                Q*S                Q                  A PRIME
1     0.21700000E 04     0.39269910E 00     0.39269910E 00     0.14986647E 03     0.79418861E 06     0.59665503E 00    PHASE
      X                  Y                  Z                  X DOT              Y DOT              Z DOT
2    -0.19160868E 08     0.89544036E 07    -0.59352598E 06    -0.98335076E 04    -0.23117790E 05     0.80830179E 03      5
      R                  THETA              PHI SMALL          V                  GAMMA              BETA
3     0.21158272E 08     0.42754032E 01     0.31106266E 01     0.25135303E 05    -0.35860506E-01     0.66130260E-01
      A*X                A*Y                A*Z                ALPHA*1            ALPHA*2            ALPHA*3
4    -0.59850615E 00     0.18766118E 02    -0.40726857E 01    -0.76481949E 00     0.14437567E 00     0.25158238E 01
      DELTA PHI*C        R DOT DOT          DELTA R            OMEGA*PI           OMEGA*YA           OMEGA*RO
5     0.15707963E 01     0.66514401E 01     0.43895000E 04     0.81897184E-03    -0.41310116E-03    -0.24260218E-03
      H                  R DOT              MAG D BAR          MAG N BAR          E*N                NEXTT3
6     0.23253300E 06    -0.90117150E 03     0.58609691E 04     0.29537611E 04     0.37805460E-01     0.23055055E 04
```

Simulation Printout (cont'd.)

RUN NO. 1 TYPICAL EARTH SINGLE SKIPOUT SIMULATION - V*O = 49,980 FPS PHASE NO. 6 PAGE NO. 9

BEGIN CONSTANT ALTITUDE

	TIME	PHI*C	PHI	Q*S	Q	A PRIME	
1	0.22296168E 04	0.31409146E 01	0.39269910E 00	0.21533556E 03	0.80643342E 06	0.18166282E 01	PHASE
	X	Y	Z	X DOT	Y DOT	Z DOT	
2	-0.19698915E 08	0.76169204E 07	-0.55721144E 06	-0.82419791E 04	-0.21291865E 05	0.32420783E 03	6
	R	THETA	PHI SMALL	V	GAMMA	BETA	
3	0.21127593E 08	0.43435637E 01	0.31133138E 01	0.22833721E 05	-0.21680062E-05	0.32967277E-01	
	A*X	A*Y	A*Z	ALPHA*1	ALPHA*2	ALPHA*3	
4	-0.36258454E 01	0.57248543E 02	-0.11453066E 02	-0.76724429E 00	0.17405702E 00	0.25381210E 01	
	DELTA PHI*C	R DOT DOT	DELTA R	OMEGA*PI	OMEGA*YA	OMEGA*RO	
5	-0.67820002E-03	0.17571549E 02	0.	0.12352733E-03	-0.45351009E-03	-0.27239447E-03	
	H	R DOT	MAG D BAR	MAG N BAR	E*N	NEXTT3	
6	0.20185450E 06	-0.49503649E-01	0.17844820E 05	0.89932797E 04	0.37805460E-01	0.22296168E 04	

	TIME	PHI*C	PHI	Q*S	Q	A PRIME	
1	0.23000000E 04	0.81974957E 00	0.82883343E 00	0.13762597E 03	0.81859961E 06	0.13521332E 01	PHASE
	X	Y	Z	X DOT	Y DOT	Z DOT	
2	-0.20186038E 08	0.62099612E 07	-0.57515628E 06	-0.57523952E 04	-0.18775496E 05	-0.79836686E 03	6
	R	THETA	PHI SMALL	V	GAMMA	BETA	
3	0.21127483E 08	0.44140552E 01	0.31131075E 01	0.19653159E 05	-0.42976593E-04	-0.39009894E-01	
	A*X	A*Y	A*Z	ALPHA*1	ALPHA*2	ALPHA*3	
4	-0.72269575E 00	0.41480726E 02	-0.13207750E 02	-0.12181810E 01	0.22100906E 00	0.24740174E 01	
	DELTA PHI*C	R DOT DOT	DELTA R	OMEGA*PI	OMEGA*YA	OMEGA*RO	
5	-0.75242535E 00	-0.10914207E 00	-0.11050000E 03	0.65019005E-04	0.49645625E-02	-0.10595028E-01	
	H	R DOT	MAG D BAR	MAG N BAR	E*N	NEXTT3	
6	0.20174400E 06	-0.84462582E 00	0.13282065E 05	0.66937818E 04	0.37805460E-01	0.23679727E 04	

Simulation Printout (cont'd.)

```
RUN NO.  1        TYPICAL EARTH SINGLE SKIPOUT SIMULATION - V*O = 49,980 FPS          PHASE NO. 7        PAGE NO.  10

 BEGIN SUB-CIRCULAR REENTRY
     TIME              PHI*C             PHI               Q*S               Q                 A PRIME
1    0.23786193E 04    0.                0.64184923E-06    0.90157163E 02    0.82734522E 06    0.10365424E 01    PHASE
     X                 Y                 Z                 X DOT             Y DOT             Z DOT
2   -0.20557886E 08    0.48257298E 07   -0.65736358E 06   -0.37992664E 04   -0.16536156E 05   -0.10589919E 04      7
     R                 THETA             PHI SMALL         V                 GAMMA             BETA
3    0.21126913E 08    0.44819385E 01    0.31096273E 01    0.17000010E 05   -0.27787109E-02   -0.61472140E-01
     A*X               A*Y               A*Z               ALPHA*1           ALPHA*2           ALPHA*3
4   -0.79648140E 01    0.32382722E 02    0.13866985E 01   -0.36307438E 00    0.26483851E 00    0.27526589E 01
     DELTA PHI*C       R DOT DOT         DELTA R           OMEGA*PI          OMEGA*YA          OMEGA*RO
5   -0.15707963E 01   -0.27659722E 01   -0.65149999E 03    0.97374787E-03    0.44152851E-07   -0.76015056E-07
     H                 R DOT             MAG D BAR         MAG N BAR         E*N               NEXTT3
6    0.20117400E 06   -0.47238053E 02    0.10182003E 05    0.51314387E 04    0.37805460E-01    0.23786194E 04

     TIME              PHI*C             PHI               Q*S               Q                 A PRIME
1    0.25000000E 04    0.                0.                0.63738685E 02    0.83671789E 06    0.17312966E 01    PHASE
     X                 Y                 Z                 X DOT             Y DOT             Z DOT
2   -0.20867359E 08    0.30339381E 07   -0.76755326E 06   -0.15262622E 04   -0.12470390E 05   -0.73889768E 03      7
     R                 THETA             PHI SMALL         V                 GAMMA             BETA
3    0.21100725E 08    0.45681054E 01    0.31048267E 01    0.12585153E 05   -0.20404610E-01   -0.56246798E-01
     A*X               A*Y               A*Z               ALPHA*1           ALPHA*2           ALPHA*3
4   -0.18841557E 02    0.52429831E 02    0.19799630E 01   -0.36307373E 00    0.26483841E 00    0.28565808E 01
     DELTA PHI*C       R DOT DOT         DELTA R           OMEGA*PI          OMEGA*YA          OMEGA*RO
5   -0.15707963E 01    0.19144263E 01   -0.65149999E 03    0.52431323E-03    0.25640893E-08    0.44977980E-08
     H                 R DOT             MAG D BAR         MAG N BAR         E*N               NEXTT3
6    0.17498625E 06   -0.25677732E 03    0.17006604E 05    0.85708427E 04    0.37805460E-01    0.27365486E 04

     TIME              PHI*C             PHI               Q*S               Q                 A PRIME
1    0.27500000E 04    0.                0.                0.78116428E 00    0.84219666E 06    0.12305345E 01    PHASE
     X                 Y                 Z                 X DOT             Y DOT             Z DOT
2   -0.20945631E 08    0.13928463E 07   -0.85932410E 06    0.51749186E 03   -0.14306616E 04   -0.53877734E 02      7
     R                 THETA             PHI SMALL         V                 GAMMA             BETA
3    0.21009472E 08    0.46460443E 01    0.31005892E 01    0.15223315E 04   -0.41125195E 00   -0.51298013E-01
     A*X               A*Y               A*Z               ALPHA*1           ALPHA*2           ALPHA*3
4   -0.28779771E 02    0.27234000E 02    0.18132103E 00   -0.36307374E 00    0.26483841E 00   -0.29577044E 01
     DELTA PHI*C       R DOT DOT         DELTA R           OMEGA*PI          OMEGA*YA          OMEGA*RO
5   -0.15707963E 01   -0.14269060E 01   -0.65149999E 03    0.74723362E-02   -0.36624824E-08    0.68118270E-09
     H                 R DOT             MAG D BAR         MAG N BAR         E*N               NEXTT3
6    0.83732749E 05   -0.60856296E 03    0.12087595E 05    0.60918031E 04    0.37805460E-01    0.27727337E 04
```

Simulation Printout (cont'd.)

```
RUN NO.  1        TYPICAL EARTH SINGLE SKIPOUT SIMULATION - V*O = 49,980 FPS              PHASE NO. 8          PAGE NO.  11

 REENTRY HAS BEEN ACCOMPLISHED
        TIME               PHI*C              PHI                Q*S                Q                  A PRIME
1       0.27793821E 04     0.                 0.                 0.32518959E 00     0.84221167E 06     0.11481831E 01     PHASE
        X                  Y                  Z                  X DOT              Y DOT              Z DOT
2      -0.20929550E 08     0.13603174E 07    -0.86035667E 06     0.55995356E 03    -0.82831512E 03    -0.19581712E 02       8
        R                  THETA              PHI SMALL          V                  GAMMA              BETA
3       0.20991349E 08     0.46475399E 01     0.31005085E 01     0.10000187E 04    -0.65753660E 00    -0.49293585E-01
        A*X                A*Y                A*Z                ALPHA*1            ALPHA*2            ALPHA*3
4      -0.32252920E 02     0.18067177E 02    -0.46670562E 00    -0.36307373E 00     0.26483840E 00    -0.27099220E 01
        DELTA PHI*C        R DOT DOT          DELTA R            OMEGA*PI           OMEGA*YA           OMEGA*RO
5      -0.15707963E 01     0.13388667E 01    -0.65149999E 03     0.86947601E-02    -0.                -0.
        H                  R DOT              MAG D BAR          MAG N BAR          E*N                NEXTT3
6       0.65610000E 05    -0.61118034E 03     0.11278654E 05     0.56841197E 04     0.37805460E-01     0.27793821E 04
```

Simulation Printout (cont'd.)

4.7.3 Input Parameter Explanation

Program Flags

TROPGN was set to zero so that constant gains (K_{11}, K_{21}, K_{12}, K_{22}) were used in phases 2 and 6. If TROPGN had been set to 1, ζ_1 and ζ_2 were set to 0.7 and τ_1 and τ_2 were set to 20, the trajectory during phases 2 and 6 would have been smoother. Better constant altitude control results from using the time-varying gains.

Trajectory Data

t_{Gi}, Δt_{Gi} - see section on Program Control - delta t_2 and ϵ_2 below.

$\beta_{(I)} = 0.698$ rad/sec = 40° sec. This maximum roll rate is close to the maximum roll rate attainable by Apollo type vehicles.

$\epsilon_S = 0.7$. This is an unrealistically large value if there is any desire to keep the vehicle in its initial flight path plane. Using this value, the vehicle went as far as 900, 000 feet out-of-plane. Better in-plane control results using values like 10^{-3}. However, since the vehicle must roll one way or the other in order to correct for out-of-plane velocity components, the normal force is pointed up (or down) more often than if the vehicle had not rolled. This can have a considerable effect on the successful re-entry region of the vehicle.

T_c, r_c, T'_c were input as 0 even though they needn't have been input at all since the program was not started in phases 2 or 3.

V_{IN} = 17, 000 ft/sec. This is about 70 percent of circular velocity where it is expected that the vehicle will not be able to remain at a constant altitude even with the normal force directed all the way up.

F_{10}, F_{11}, F_{12}, F_{20}, F_{21}, F_{22} were set to zero since no better skipout control policy was available.

r_s was set equal to the initial radial distance so that the free-fall phase (4) will start when the skipout control phase (3) gets the vehicle up to a height of about 400, 000 ft.

t_3 and t'_3 = 250 sec. This value was guessed at to allow the vehicle to lose speed in the constant altitude phase for about 170 seconds.

C_{vpc} and C_{apc} were set to zero (not used anyway since TRACC = 0) since the change to constant altitude control was desired at $\dot{r} = 0$. It may be more desirable to change to constant altitude control sooner if the commanded roll angle in the constant altitude control phase (1 or 5) is greater than $\pi/2$. This may be accomplished by choosing appropriate values for C_{vpc} and C_{apc}, and setting TRACC equal to 1.

Program Control

$\delta t_1 = 0.5$ and $\epsilon_1 = 0.001$ were set to these values because they seemed reasonable. For this particular run time reached a value of about 7000 seconds. Since the computer used had 8 significant figures, 4 were left to the right of the decimal. Thus an ϵ_1 of .0001 is large enough to prevent looping in the integration routine.

$\delta t_2 = 64$ and $\epsilon_2 = 0.01$. The parameters δt_2 and ϵ_2 are used only in phase 4 (free-fall phase). If phase 4 is started at an altitude of 400,000 feet, the effect of the atmosphere will be negligible and the vehicle's trajectory will be that of an ellipse. For this reason, the step size can be made large in the integration routine. This will allow real time to be much shorter than the trajectory time in phase 4. For these same reasons, the nominal control calculation interval (Δt_{Gi}) should also be made large. In order that the integration routine not be left more often than intended, the Δt_G used in phase 4 should be an integer multiple of δt_2. In this run, Δt_G was made equal to δt_2. The problem comes in inputting the proper values of t_G so that the large Δt_G does not get used in phases 3 or 5. The best procedure for determining proper values of t_G is by experience.

Trajectory Constraints

$G_{max} = 10$ was used because it is the standard maximum level of acceleration (in earth g's) at which a pilot can remain usefully conscientious.

$r_m = 21.425 \cdot 10^6$. This radial distance is about 100,000 feet above the initial radial distance. If the vehicle is at this height, $\dot{r}$ is positive and the program is in phases 1, 2, 5, or 6, it is assumed that an unintended skipout has occurred and the program will terminate on special condition number 4.

$r_{ma} = 23.36 \cdot 10^6$. This is the radial distance of the lowest Van Allen belt from the center of the earth. If the r_a (apocenter distance) calculated at the beginning of phase 4 exceeds this value, the program will terminate on special condition number 1.

4.7.4 Characteristics of Phase 4

If r_s is set equal to the initial radial distance, we may assume that atmospheric effects will be negligible and that the trajectory will be an ellipse with a focus at the center of the re-entry planet. Thus, the velocity and magnitude of the flight path angle will be the same at the beginning and end of phase 4 (phase 4 begins and ends when $r = r_s$). This may be helpful in running the program since it may be possible to know what will happen to the trajectory by looking at the velocity and flight path angle at the beginning of phase 4 (i.e., the run may be terminated at the beginning of phase 4).

5.0 OPERATOR'S AND PROGRAMMER'S GUIDE

5.1 GENERAL INFORMATION

Program 133 was originally written by the Los Angeles Laboratory of AC Electronics in FORTRAN IV for use on an IBM 7040.

Program 133 is a straightforward program which requires no overlay and does not read or write tapes. All one has to do is to add the data deck on the end of the problem deck (source or object) with proper control cards.

It should be noted that any attempt to compile and/or execute the program under any system different from that described below may require modifications.

5.2 DECK ARRANGEMENT

The order of the FORTRAN decks that comprise 133.0 is shown by the compilation listing as well as by the 8 1/2 by 11 vellum 407 listing, but will also be enumerated here in condensed form.

DECKS	DESCRIPTION
133	Driver
COMPN	Computes nominal trajectory
INITO	Initializes nominal trajectory
COMBRA	Computes reference body axes
NOMIN	Controls nominal trajectory
NOMCOM	Computes guidance control angle, φ_c
COMPHI	Computes roll angle φ
COMAER	Computes aerodynamic forces
COMACC	Computes acceleration
SUBVAL	Evaluation of next time and constraints
COMNT	Computes next time
ATUDE	Computes vehicular attitude variables
OUTCON	Evaluates program state
DASTOR	Computes output variables and call print subroutine
SNP	Computes elliptical radii
SOUT2	Prints the output
OUTNI	Prints out program inputs
EVAL	Evaluates trajectory derivatives
PRC	Dummy subroutine (not used) Required by integration subroutine
INPUT	Reads input data
ACINTG	Integrates position, velocity and evaluation parameters

5.3 MACHINE CONFIGURATION

Program 133 was compiled and executed on an IBM 7094 Mod II computer using the AVCO IBM 7094 IBSYS operating system supplied by NASA/ERC.

Table 5-1 contains the unit table configuration used under this system.

FUNCTION	SYMBOL	PHYSICAL	LOGICAL FORTRAN IV
Library 1	SYSLB1	A1	
Library 2	SYSLB2	Unassigned	
Library 3	SYSLB3	Unassigned	
Library 4	SYSLB4	Unassigned	
Card Reader	SYSCRD	RDA	
On-line Printer	SYSPRT	PRA	
Card Punch	SYSPCH	A0	
Output	SYSOU1	A3	6
Alternate Output	SYSOU2	A3	
Input	SYSIN1	B3	5
Alternate Input	SYSIN2	B3	
Peripheral Punch	SYSPP1	B4	7
Alt. Peripheral Punch	SYSPP2	B2	
Check Point	SYSCK1	B5	
Alternate Check Point	SYSCK2	B5	
Utility 1	SYSUT1	A4	1
Utility 2	SYSUT2	B1	2
Utility 3	SYSUT3	A2	3
Utility 4	SYSUT4	B2	4
Utility 5	SYSUT5	Unassigned	
Utility 6	SYSUT6	Unassigned	
Utility 7	SYSUT7	Unassigned	
Utility 8	SYSUT8	Unassigned	
Utility 9	SYSUT9	Unassigned	

ATTACHED UNITS NOT ASSIGNED

A5	B6
A6	B7
A7	B8
A8	B9
A9	B0

INTERSYSTEM RESERVE UNITS

None

Table 5-1. Version 13 Unit Table Configuration

5.4 PROGRAM TERMINATIONS

There are three types of program terminations that could occur during a run, each of which is discussed below.

5.4.1 Input Card Errors

These are errors on the input cards that prevent the input routine from interpreting the data on the card properly, and are usually the result of keypunching mistakes or improperly prepared data.

Upon encountering an error of this type, the input routine prints the card in error followed by the comment "ERROR ON THE PRECEDING CARD".

5.4.2 Terminations Occurring During Calculation

The condition/error codes and messages which terminate a case are as follows:

RUN ENDS ON SPECIAL CONDITION N

The possible condition/error codes that could be printed in the above format are listed below.

CONDITION CODE (N)	EXPLANATION
1	Free-fall elliptical radius too large (beginning of phase 4)
2	Initial flight path angle for free-fall too large (beginning of phase 4)
3	Initial flight path angle for the free-fall too small (beginning of phase 4)
4	Vehicle radial distance too large (phases 1, 2, 5, and 6 only)
5	Acceleration is too large (phases 1, 2, 5, and 6 only)
6	Skipout not possible because of low velocity (phase 3 only)
7	Time to integrate to less than current time. (Error Condition)

5.4.3 Abnormal Errors

Examples of errors falling in this class are:

1. Overflow or too many underflows (if the system has a limiting number);
2. Time estimate is exceeded and the job is terminated by the system before completion.

5.4.4 Terminating Comments

The three possible types of terminating comments are:

1. Messages as described in 5.4.1, 5.4.2, and 5.4.3
2. RE-ENTRY HAS BEEN ACCOMPLISHED
   (This comment implies successful end of phase 7)
3. END NOMINAL TRAJECTORY
   (This comment implies successful end of case — ends on input time.)

6.0 REFERENCES

"REENTRY"

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7.0 APPENDICES

7.1 TRANSLITERATIONS

1. FORTRAN IV to Math

2. Math to FORTRAN IV

1. FORTRAN IV to Math

AA (I)	$\underline{f}$	CAPC	C_{apc}
ABAR	$\underline{a}$	CCH	C_H
AC	$\underline{a}$	CD	C_D
AC (I) I=1, 2, 3	$\ddot{X}, \ddot{Y}, \ddot{Z}$	CDZE	C_{D_o}
AFIVE (I, J)	A_5	CE1	C_{e1}
AFOR (I, J)	A_4	CE2	C_{e2}
AICH	h	CFIV	C_5
AL(1)	α_1	CFOR	C_4
AL(2)	α_2	CK11	K_{11}
AL(3)	α_3	CK12	K_{12}
ALFA	α	CK13	K_{13}
ALF1	α'	CK21	K_{21}
ALF2	α''	CK22	K_{22}
ALZE (I) I=1, 2, 3	α_{i_o}	CK23	K_{23}
ATHR (I, J)	A_3	CKONE	K_1
ATOO (I, J)	A_2	CKPHI	K_φ
		CKTHR	K_3
BATA	β'	CKTWO	K_2
BETA	β	CN	C_N
BPHI	β_φ	CNAL	C_{N_α}
		CTHR	C_3
		CTWO	C_2
		CVPC	C_{vpc}

$\underline{D}$	DEE (I) 1, X 2, Y 3, Z
D	DEEM
DELPHI	$\Delta\varphi_c$
DELT1	δt_1
DELT2	δt_2
DTGO(I)	Δt_G
DTPR(I)	Δt_p
EDOTN	$\dot{E}_n$
EE (I)	E_i
EFI	ϕ
EF0	F_0
EF1	F_1
EF2	F_2
EF10	F_{10}
EF11	F_{11}
EF12	F_{12}
EF20	F_{20}
EF21	F_{21}
EF22	F_{22}
ELA	a_e
ELE	e
ELP	p
EM	M
EMU	μ
EN	$\underline{N}$
ENM	N
EPI1	ϵ_1
EPI2	ϵ_2
EPS	ϵ_s
ESS	S
ESUB(I)	E_i
FBAR	a
FPRI	a'
GEAR	g_e
GEE	g
GMAX	G_{max}
GSURF	g_o

OMEG(1)	ω_{PI}
OMEG(2)	ω_{RO}
OMEG(3)	ω_{YA}
OMPHI	ω_{φ}
PHI	φ, φ_i
PHI11	φ_{11}
PHI21	φ_{21}
PHIC	φ_c
PHIC1	φ_{c1}
PHIC3	φ_{c3}
PHIL	φ_{i-1}
PHIZ	φ_o
PIZ(I)	$\underline{P}_{IO}$
QUE	Q
R(I)	$\underline{r}$
RA(I)	$\underline{r}_a$
RAD	r
RADA	r_a
RADC	r_c
RADM	r_m
RADP	r_p
RADS	r_s
RBAR	$\underline{r}$
RDDOT	$\ddot{r}$
RDOT	$\dot{r}$
RHO	ρ
ROSUR	ρ_o
ROZ(I)	$\underline{R}_{O_o}$
RSUBN	R_N
RSURF	R
RT(I)	$\underline{r}_t$
RVA(I)	$\underline{V}_a$
RVZE(I) I = 1, 2, 3, 4, 5, 6	$X_o, Y_o, Z_o,$ $\dot{X}_o, \dot{Y}_o, \dot{Z}_o$

SKH	k_H
SMLM	m
SMLN	n
SMLQC	q_c
SMLQR	q_r
SMLQS	q_s
SPH	p_H
SQ1	q_1
SQ2	q_2
SR(2)	λ
SR(3)	μ
TCPR	T'_c
TEND	t_{END}
TGO(I)	t_{Gi}
THATA	θ
TIMEC	T_c
TIME3	t_3
TIME4	t_4
TNEXT(I)	$NEXTT_i$
TNOW	t, t_i
TPR(I)	T_{pi}
TZERO	t_o
UP(I)	$\underline{U}_p$
UR(I)	$\underline{U}_r$
UU(I)	$\underline{U}_u$
UV(I)	$\underline{U}_v$
V(I)	$\underline{V}$
VA(I)	$\underline{V}_a$
VBAR	$\underline{V}$
VEDOT	$\dot{V}$
VEEA	V_a
VEND	V_{END}
VIN	V_{IN}
VT(I)	$\underline{V}_t$

2. Math to FORTRAN IV

$\underline{a}$	AC, ABAR
a	FBAR
a'	FPRI
a_e	ELA
A_o	RVZE (6)
A_2	ATOO(I, J)
A_3	ATHR(I, J)
A_4	AFOR(I, J)
A_5	AFIV(I, J)
C_{apc}	CAPC
C_{vpc}	CVPC
C_D	CD
C_{D_o}	CDZE
C_3	CTHR
C_5	CFIV
C_N	CN
C_{N_α}	CNAL
C_2	CTWO
C_4	CFOR
C_{e1}	CE1
C_{e2}	CE2
C_H	CCH
$\underline{D}$	DEE (I) 1, X 2, Y 3, Z
D	DEEM
e	ELE
E_i	ESUBI, EE (I)
E_n	ESUBN
$\dot{E}_n$	EDOTN

$\underline{f}$	AA(I)	g	GEE	h	AICH
F_0	EF0	g_e	GEAR		
F_1	EF1	g_o	GSURF		
F_2	EF2	G_{max}	GMAX		
F_{10}	EF10				
F_{11}	EF11				
F_{12}	EF12				
F_{20}	EF20				
F_{21}	EF21				
F_{22}	EF22				

k_H	SKH	M	EM	n	SMLN
K_1	CKONE	m	SMLM	$\underline{N}$	EN
K_2	CKTWO			N	ENM
K_3	CKTHR			$NEXTT_i$	TNEXT(I)
K_{11}	CK11				
K_{12}	CK12				
K_{13}	CK13				
K_{21}	CK21				
K_{22}	CK22				
K_{23}	CK23				
K_ϕ	CKPHI				

p	ELP
p_H	SPH
$\underline{P}_{IO}$	PIZ (I)
q_1	SQ1
q_2	SQ2
q_c	SMLQC
q_r	SMLQR
q_s	SMLQS
Q	QUE
$\underline{r}$	R (I), RBAR
$\underline{r}_t$	RT (I)
r	RAD
$\dot{r}$	RDOT
$\ddot{r}$	RDDOT
$\underline{r}_a$	RA (I), RVA (I)
r_a	RADA
r_c	RADC
r_m	RADM
r_{ma}	RAMAX
r_p	RADP
r_s	RADS
R	RSURF
R_N	RSUBN
$\underline{R}_{O_o}$	ROZ (I)

S	ESS	t_o	TZERO	$\underline{U}_p$	UP(I)
		t, t_i	TNOW	$\underline{U}_r$	UR(I)
		t_3	TIME3	$\underline{U}_u$	UU(I)
		t'_3	TTPR	$\underline{U}_v$	UV(I)
		t_4	TIME4		
		t_{END}	TEND		
		T_{pi}	TPR(I)		
		T_{G_i}	TGO(I)		
		T_c	TIMEC		
		T'_c	TCPR		

V_o	RVZE(4)
$\underline{V}_a$	VA(I), RVA(I)
V_a	VEEA
$\underline{V}$	VBAR, V(I)
V	VEE
$\underline{V}_t$	VT(I)
V_{IN}	VIN
V_{END}	VEND
$\dot{V}$	VEDOT
X_o, Y_o, Z_o	RVZE(I) I = 1, 2, 3
$\dot{X}_o, \dot{Y}_o, \dot{Z}_o$	RVZE(I) I = 4, 5, 6
$\ddot{X}, \ddot{Y}, \ddot{Z}$	AC(I) I = 1, 2, 3
α	ALFA
α'	ALF1
α''	ALF2
α_1	AL(1)
α_2	AL(2)
α_3	AL(3)
α_{io}	ALZE(I) I = 1, 2, 3

β	BETA	ω_{φ}	OMPHI	τ_1	CK12
β'	BATA	ω_{PI}	OMEG(1)	τ_2	CK22
β_{φ}	BPHI	ω_{RO}	OMEG(2)		
		ω_{YA}	OMEG(3)	ζ_1	CK11
ϵ_1	EPI1			ζ_2	CK21
ϵ_2	EPI2	φ, φ_i	PHI		
ϵ_s	EPS	φ_{i-1}	PHIL		
		φ_o	PHIZ		
$\Delta\varphi_c$	DELPHI	φ_c	PHIC		
Δt_p	DTPR(I)	φ_{c1}	PHIC1		
Δt_G	DTGO(I)	φ_{c3}	PHIC3		
		φ_{11}	PHI11		
δt_1	DELT1	φ_{21}	PHI21		
δt_2	DELT2				
		ϕ	EFI		
γ	GAMMA				
γ_{max}	GAMAX	ρ	RHO		
γ_{min}	GAMIN	ρ_o	ROSUR		
λ_o	RVZE(2)	θ	THATA		
λ	SR(2)				
μ	SR(3), EMU				

7.2 PROGRAM LISTING

The original of the program listing is supplied with the program deck.